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DESIGN OF THE PASSIVE PERSONAL DOSIMETER
FOR MINERS USING AN ALLYL DIGLYCOL
CARBONATE PLASTIC
PHASE 1: BASIC AND FEASIBILITY STUDY

by

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RESEARCH REPORT

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ABSTRACT

The report summarizes the results of the feasibility study on the design and development of a passive personal dosimeter incorporating an allyl diglycol carbonate plastic (CR39) detector, for use by uranium miners. Based upon the feasibility study, a passive personal dosimeter using a capacitor-type electrostatic enhancement device has been designed. Preliminary tests indicate that the prototype could be used in the mine environment to differentiate radon and thoron daughters with a detection efficiency comparable to that of a typical active device. Further study is required, however, into the possible influence in the mine environment of local variations in charged fraction, upon the calibration of this dosimeter.

RÉSUMÉ

Le présent rapport résume les résultats de l'étude de faisabilité concernant la conception et la mise au point d'un dosimètre individuel passif pour mineurs d'uranium. Le dosimètre utilise un détecteur de plastique fait de carbonate d'allyldiglycol (CR 39). À partir des résultats de l'étude de faisabilité, on a conçu un dosimètre individuel passif utilisant un condensateur électrique produisant un effet d'attraction électrostatique. Les essais préliminaires ont indiqué que le prototype pourrait être utilisé en milieu minier pour mesurer séparément les produits de filiation du radon et du thoron, avec une capacité de détection comparable à celle d'un dosimètre actif. Des études supplémentaires sont cependant nécessaires pour déterminer l'influence possible des variations locales de la fraction d'aérosols chargés électriquement sur l'étalonnage du dosimètre.

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1. INTRODUCTION

1.1 Scope

This final report describes the test program as required by the Supply and Services, Canada, Contract No. 1450.87055-2-4056, "Design of the Passive Personal Dosimeter for Miners Using an Allyl Diglycol Carbonate Plastic". The Allyl Diglycol Carbonate material used as the detector in this project is manufactured under the trade designation CR39 by American Acrylics and Plastics.

1.2 Objective

The overall objective of this project is to design a passive personal dosimeter for uranium miners which is comparable with the corresponding active dosimeter in the following characteristics:

- (1) Sensitivity;
- (2) Quality Control (uniformity of response);
- (3) Ability to differentiate radon and thoron daughters.

The work covered in this report pertains to the feasibility study mentioned under Objective in the Statement of Work (Appendix B).

2. BACKGROUND

In the past ten years, significant work has been carried out on the passive personal dosimeter for uranium miners, of which the most well known are those of Domanski⁽¹⁾ and Benton⁽⁵⁾. R.A.D., in coordination with AECS, has been constantly looking at the latest developments in this interesting subject.

2.1 Past Work

In Section 2.1, the work of Domanski (Section 2.1.1) and Benton (Section 2.1.2) is described briefly. In Section 2.2, further R.A.D. comments on the current status are given.

2.1.1 Domanski's Work⁽¹⁾

Domanski followed the "volume source" and "total absorption" approach for the design of the passive dosimeter. The "volume source" method assumes that a monoenergetic alpha source is distributed uniformly throughout a homogeneous medium. If an alpha counter is placed on the surface of a volume source, it detects alphas in the energy range.

$$0 < E_{\alpha} < E_{\alpha M}$$

where $E_{\alpha M}$ is the energy of the monoenergetic source in the region of the medium.

$$d_M > d > 0$$

where d_M is the maximum range of the monoenergetic alpha source inside the medium.

A basic requirement for the "volume source" method is homogeneity, that is, the concentration of the alpha emitter should be constant throughout the volume of the medium being studied. Homogeneity is important because if it is not present, the theoretical estimation of the detection efficiency will be complicated. This homogeneity assumption is close to reality for alpha emitters existing in the lithosphere or hydrosphere. For alpha emitters in the atmosphere, however, this assumption may not hold if plate-out exists. Plating out of alpha emitters onto an external surface tends to give a lower concentration of alpha emitters in the air in the area above the external surface as compared with other layers in the atmosphere. This creates non-homogeneity. Homogeneity can thus be disturbed by local variations caused by surfaces within the volume under consideration. Since plate-out is difficult to avoid, care should be taken in using the "volume source" condition.

The "total absorption" method is effective in differentiating alpha emitters of different energies, for instance, radon and thoron daughters. However, for a volume source which presents a continuous energy spectrum of $0 < E_\alpha < E_{\alpha M}$, the absorber would not only stop alphas from the lower energy group but also some of the alphas from the higher energy group that have been degraded in energy, thus lowering the efficiency for detecting the alphas from this group.

Taking RaC' ($E_\alpha = 7.7$ MeV) and ThC' ($E_\alpha = 8.8$ MeV) as an example, alphas from RaC' will show a continuous spectrum of $0 < E_\alpha < 7.7$ and alphas from ThC' will show a continuous spectrum of $0 < E_\alpha < 8.8$. If an absorber is used to stop alphas from RaC', it will also stop alphas from ThC' in the energy range $0 < E_\alpha < 7.7$ and let alphas in the range $7.7 < E_\alpha < 8.8$ pass through. Assuming homogeneous distribution of ThC' in air, then only $\frac{8.8 - 7.7}{8.8}$ or 12.5% of the total ThC' in air could be detected.

Domanski used LR 115 type II (a nitrocellulose manufactured product by Kodak Pathe', France) for the passive detector. One of the characteristics of this detector is that the size of the tracks formed by alphas at incident angles equal to or greater than 30° to the perpendicular is very small⁽¹³⁾. Extreme care should be taken to avoid loss of counts. Fig. 1 compares the size of the tracks formed by 3 MeV alphas at incident angles of 0° and 30° from the perpendicular. The lower detection efficiency of the LR115 type II detector can be understood better in comparison with the detector CR39 as will be shown in Section 5.1.1. Alpha tracks in CR39 can be easily identified from 1 MeV to 5 MeV after 2 hours of etching and tracks of alphas with different angles of incidence from 0° to 55° can be detected with the same efficiency (Fig. 59).

Theoretically, if both LR115 type II and CR39 detectors are exposed to the same volume source containing RaA only ($E_{\max} = 6$ MeV), the difference in the detection efficiency can be illustrated as follows: For the energy spectrum CR39 registers alphas from 0 to 6 MeV while LR115 type II registers from 0 to 4 MeV only. This makes the efficiency of LR115 type II one-third less than that of CR39. For the angle of incidence, LR115 type II only registers tracks from 0° to 30° while CR39 registers from 0° to 55° . This makes the efficiency of LR115 type II roughly one-half less than that of CR39. Considering both energy spectrum and angle of incidence, overall detection efficiency of LR115 type II will be expected to be one-third that of CR39. The low detection efficiency of LR115 type II in comparison with CR39 has been reported⁽⁴⁾ based upon experimental results.

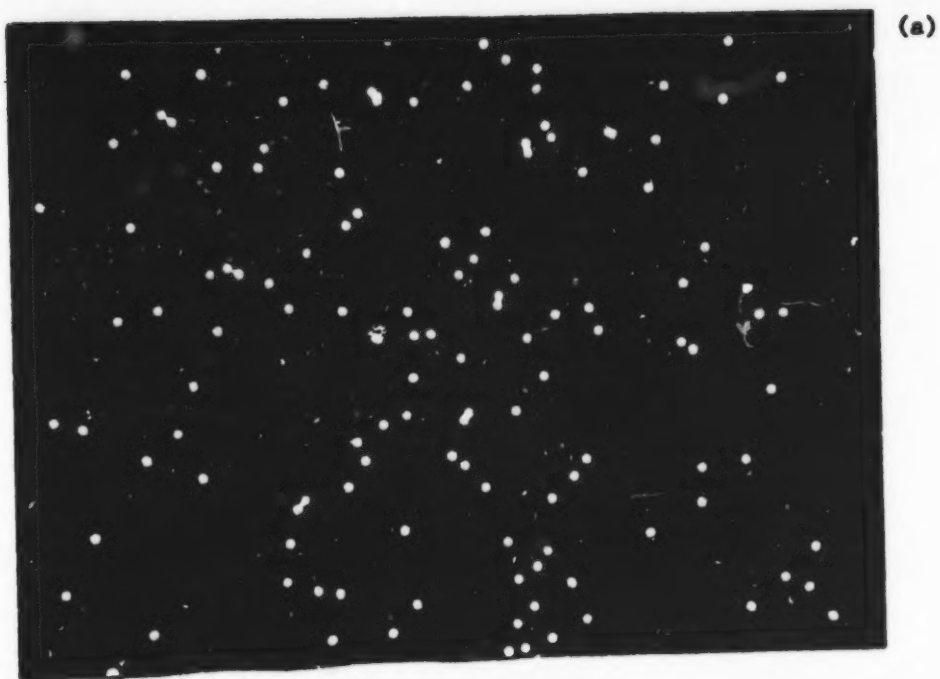


Fig. 1 Tracks of 3 MeV alphas at an incident angle of (a) 0° and (b) 30° from the perpendicular.

Domanski did excellent work on the general analysis of the "volume source" and the "total absorption" methods for passive dosimeters. However, he accepted that his approach was not altogether successful, judging from the results of his experimental verification. The reason why he was not satisfied with the results is that the uncertainty could not be improved beyond 30%. It is considered that the low efficiency of his system may account for 10% of the overall uncertainty. The low efficiency can be attributed to the use of LR115 type II as the passive detector and the use of an absorber for the volume source.

2.1.2 Benton's Work (5)

Benton made a good choice for his passive dosimeters, with the use of CR39 as the detector for the radon diffusion chamber (RDC) and CA-80-15 for the ambient alpha detector. CR39 was chosen to improve the detection efficiency and CA-80-15, a nitrocellulose detector from Kodak, for the purpose of avoiding the detection of alphas plated out on the detecting surface. Alpha emitting sources which emit high-energy alphas usually exist close to the detecting surface. These are plated out on the surface of the detector without the usual air column energy degradation. The nitrocellulose detector does not register those alphas with energies higher than 4 MeV.

Benton tested two approaches for obtaining Working Levels - one using the results obtained with the ambient alpha detector and another using those obtained with the RDC.

The problem arising from the use of the ambient alpha detector was contamination by dust on the detector surface. According to Benton, there is no simple effective way of shielding the ambient alpha detector. Probably the reason why Benton did not use a thin film to cover the detector from direct contact with the atmosphere is that it would reduce further the detection efficiency of the CA-80-15 used for the ambient detector. Another possible consideration is that nitrocellulose usually carries an initial charge and it would be even more complicated to cover it with another insulator because of electrostatic induction.

If the results using the RDC are adopted, the value of Working Level (WL) can be indirectly inferred on condition that the Working Level ratio* is available. Benton suggested that the problem could be solved by determining a standard value of the Working Level ratio. Theoretically, if we consider that the radon daughters produced by the radon in the mine will be partitioned into two parts, - one plated out on the walls of mine cavity and another attached to the aerosols in the mine environment, then the Working Level ratio will be strongly site-dependent and therefore it will be difficult to have a standard value. As will be mentioned in Section 2.2.2, the standard value of the Working Level ratio as suggested by Benton is possibly applicable to mines with high density of dust or aerosols. However, these values may not generally hold true.

As a final remark on Benton's suggested methods, it is considered that one of the main concerns for both the ambient alpha and RDC detection methods is still the inadequate counting statistics. For the RDC method, this aspect will be demonstrated in Section 4.1.3.

*Working Level ratio is defined as the ratio of WL to the radon concentration in the atmosphere.

2.2 Comments on the Current Status

Based upon what has been done in the past, it can be concluded that the unsatisfactory test results are primarily due to:

1. Very low detection efficiency,
2. Disadvantages introduced by the volume source method.

In view of this, it is suggested that further tests should concentrate on the following:

1. Improvement in the counting efficiency
2. Simplification of the source geometry
3. Local calibration with respect to an active dosimeter

The last suggested item is necessary because for the passive dosimeter, it is difficult to have a reliable estimation of the detection efficiency (Section 2.2.1). Since the detection efficiency of the active dosimeter, for instance, CEA dosimeter, can be obtained theoretically to a certain precision and has been well verified experimentally, calibration of the passive dosimeter with respect to the active dosimeter is suggested.

2.2.1 Improvement of the Counting Efficiency

A primary defect of the passive monitor is its low detection efficiency. At a Working Level of 0.1, for instance, the track density for RaC' obtained by a CEA-type active personal dosimeter, accumulated over one working month with a flow rate of four litres per hour, will be approximately $55/\text{mm}^2$. For a passive system the sampling volume can be visualized as a small volume of air which is bounded by a base of the same dimension as the detector and a height equal to the maximum range of the alphas in the air. The efficiency of this passive system may be 10 to 100 times less than that of the active detector described above, depending on how frequently the position of the passive detector is changed. Changes of position should be considered because the moving detector acts as an extended substrate for collection.

A passive detector could, therefore, accumulate at most 5 tracks/ mm^2 . These five counts will include alphas of all angles and energies. As was already described in both Sections 2.1.1 and 2.1.2, the passive detector may lose some of these counts, leading to even lower efficiencies.

In order to make a statistically significant measurement, it is of primary importance to improve the detection efficiency of the passive detector. Three ways to do this include:

1. The use of CR39 instead of LR115 type II for the passive detector, as described in Section 2.1.1,
2. The use of electrostatic means, e.g. electrets or capacitors, to produce the required enhancement of alpha emitter collection,
3. The use of a larger detecting area.

2.2.2 Simplification of the Source Geometry

Alpha-emitting sources exist in nature as volume-distributed sources. In a volume source, alpha particle energy degradation must be taken into account, whereas in a plane source, each alpha emitting nuclide can be taken as monoenergetic. Analysis would be very much simplified if a plane source geometry could be approached. There are several ways to approach this condition. For example, in an active dosimeter, this is done by collecting aerosol samples on the surface of a filter paper. It is attempted in this project to use electrostatic forces to enhance the collection of charge-carrying aerosols on the surface of a plastic film which has been charged to an appropriate electrostatic potential. It should be emphasized here that, instead of avoiding plate-out as is the usual practice for a passive dosimeter, it is attempted to force plate-out in order to approach the plane source condition.

Another feature of the electrostatically induced plate-out method is that the piece of plastic film (either aluminized or not) required to carry the electric field, can be used as part of the alpha particle absorber and at the same time, act as an effective shield for the detector.

A recent publication (6) from EML indicated that, in the mine atmosphere (with aerosol density $>10^5$ particles/ml), as high as 96% of the radon (thoron) progeny will be attached to the aerosols. This means that the Working Level ratio is close to the saturation case and may not vary greatly. Benton's suggestion may then be a reasonable approach using the RDC detection method.

One thing, however, should be considered - the aerosol density is not necessarily high inside the uranium mine. For instance, the aerosol density in a large stope in the Denison mines may not be high at all.

As already mentioned, the EML results mean that in the typical mine atmosphere, 96% of the radon (thoron) progeny is attached to the aerosols and only 4% is plated out on the wall. Under this condition, local variation due to plate-out is negligible. The only factor contributing to the local variation is the possible spatial variation of the charge fraction of different alpha emitters. With the proper electrostatic enhancement for instance, using the plane source method, higher detection efficiency and less local effect determination of the alpha activities in the atmosphere may be expected.

2.2.3 Local Calibration with Respect to an Active Dosimeter

The latest work from a research group at the University of Toronto (7) shows some results of charged fraction measurements in an Elliot Lake uranium mine. The daily averages of the charged fractions measured at different positions in the mine were $6.3 \pm 6.2\%$ and $6.1 \pm 11.3\%$ for RaC and $10 \pm 8.3\%$ and $12.7 \pm 23.5\%$ for ThB. Although the standard deviations are high, the results indicate that there is the possibility that the charged fraction for a particular alpha emitter is not too position-sensitive. The concentration ratios of RaC to ThB were 30 ± 16.2 for one position and 83 ± 73 for the other. Again, the results do not definitely indicate that they are position-sensitive because the dispersion of the second measurement is large.

Although the above results appear to support the plane source approach, a definite conclusion cannot yet be given. A careful and extensive measurement of the ratio of RaC' to ThC' in stopes of different sizes and conditions in uranium mines is necessary.

Since an active dosimeter is only slightly influenced by the local effect, mainly due to the charged fraction difference, it would be practical and advisable to calibrate the passive dosimeter with respect to an active dosimeter in the same region.

The basic consideration which will justify this local calibration method is the extent of the area which can be assumed for the passive dosimeter to be virtually free from the local effect. If this area is limited, there will be restrictions imposed on the use of the passive dosimeters. The versatility of the method suggested in this project depends very much upon the results of investigations into this spatial uniformity.

3. AIM OF THE PROJECT

The aim of the project is to study the feasibility of designing and developing a passive personal dosimeter for use by uranium miners. Based upon the current status as was described in Section 2, two approaches can be made:

- (1) The plane source method
- (2) The volume source method

Although the plane source method is preferred in this project, there is the open question on the extent of area which can be assumed for the passive dosimeter to be virtually free from the local plate-out effect. Therefore, the volume source approach cannot be completely disregarded in this feasibility study.

In the statement of work for this project (Appendix B), the primary scope of this "basic test" is to accumulate the following information:

- (1) How to enhance collection efficiency for Rn/Pn daughters - The use of an electret for enhancement is the first priority.
- (2) How to achieve higher detection efficiency and differentiation of radon-choron daughters by using CR39 detector - This will involve energy calibration and use of the total absorption method.
- (3) How to achieve higher detection efficiency with the radon diffusion chamber - This is involved with the radon determination if the "volume source method" is adopted. The reason why radon measurement is not important for the plane source method is that radon is not charged and therefore the efficiency of its detection should not be increased by the electrostatic enhancement device.

For the volume source method, radon can only be differentiated from RaA by the total absorption method. Since alphas emitted by Rn and RaA have an energy difference of only .5 MeV, the detection efficiency for RaA will be too low if total absorption of alpha particles from Rn is attempted. One possible method is to attempt to register both Rn and RaA on the ambient alpha detector and register Rn only using the radon diffusion chamber.

4. EXPERIMENTAL DESIGN INCLUDING METHODOLOGY AND DESCRIPTION OF INSTRUMENTS

Based upon the statement of work described in the last section, instruments were specially designed for the purpose of accumulating necessary experimental information for the feasibility study. Instruments are described following, as close as possible, the sequence of the statement of work - namely basic equipment, electret charging, detector calibration, electrostatic enhancement, alpha particle differentiation and mine test equipment.

4.1 Basic Equipment

In this section, the following three instruments are described:

1. Radon (thoron) chamber
2. Stable battery-operated pump
3. Radon diffusion chamber

4.1.1 Radon (Thoron) Chamber

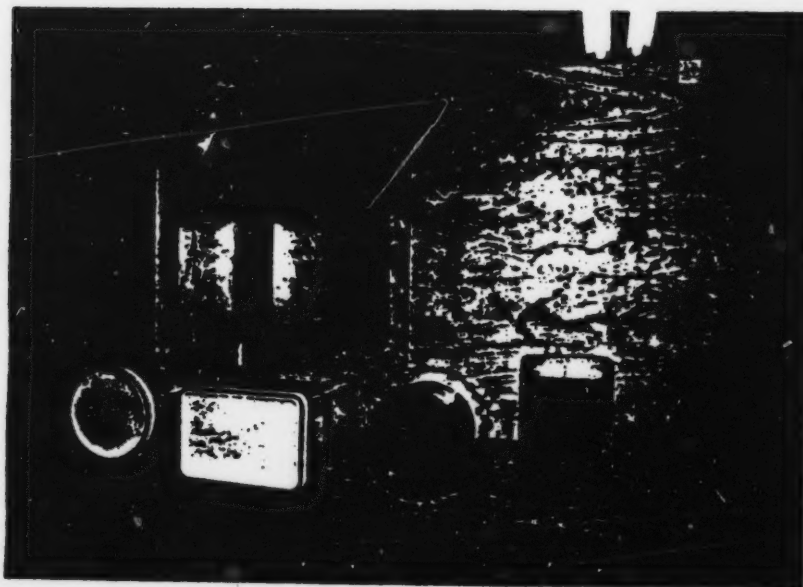


Fig. 2 The radon (thoron) chamber.

The RAD radon (thoron) chamber has an accessible working volume of 900 L and an overall effective volume of approximately 1100 L. The working volume can be easily increased to 2000 L by means of a simple extension.

The chamber walls are of $\frac{1}{2}$ " plywood, lined with galvanized sheet steel. All access points to the interior are through the front face which is 1.2 m wide and 0.6 m high. The access points are:

1. a transfer port to allow the introduction of objects up to ~ 8 cm x 15 cm x 10 cm with minimal interference with the active volume.
2. a plexiglass viewing window, ~ 36 cm x 25 cm, removable to allow servicing of the interior or the introduction of large pieces of apparatus.
3. A service panel, ~ 13 cm x 18 cm, with holes and plugs for tubing, cables, etc.

There are two glove ports (13 cm dia.) fitted with large gauntlets (46 cm long).

The source of radon (thoron) is a sample of tailings from a uranium mine in the Elliot Lake area. This source is contained in a 50 L drum fitted with an air circulating fan. The radon (thoron)- enriched atmosphere is pumped from this volume into the main working volume of the chamber.

4.1.2 Stable Battery-operated Pump

For the past three years, RAD has been engaged in the design of a battery-powered mechanically stable pump (i.e. no electronic feedback control required) which does not need a flow rate check. This pump will repeat the initial and subsequent flow rate to within 10% after each charging of the battery. It was found that this performance would be feasible using a special diaphragm pump with the following improvements:

1. A special buffer chamber to smooth out the air flow through the valve.
2. An air-tight valve chamber.
3. A special rubber valve which tightly closes the air inlet and exhaust.
4. A special rubber valve which operates smoothly in the required temperature range and dusty conditions. (Currently, only the valve used in the Dupont pump has a reasonably good resistance to dusty conditions.)

Two battery-operated pumps, with flow rates of 36 L/h and 10 L/h respectively, were designed for this project, based on the improvements mentioned above. The pumps would continuously operate for fourteen days after charging, using the ordinary miner's head light battery shown in Fig. 3.

Fig. 4 is the plot of the measured flow rate for both pump #1 (36 L/h) and pump #2 (10 L/h) versus the number of days after charging. For each of the pumps there are two curves plotted, one solid line and one dotted line. Each represents measurements taken for fourteen days after fresh charging. The flow rates were measured every day using a bubble type flowmeter.

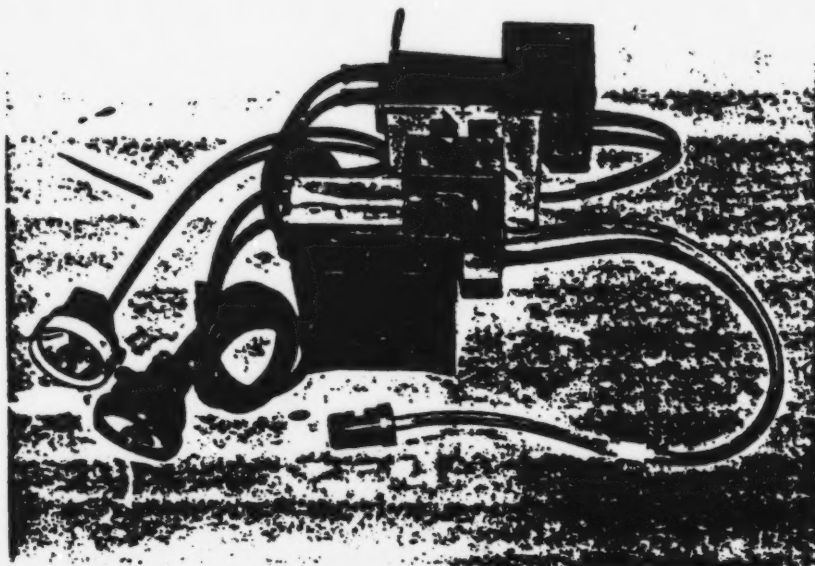


Fig. 3 Battery operated pumps

4.2.3 Radon Diffusion Chamber (RDC)

In order to improve the efficiency of the radon diffusion chamber, a plastic version of the diffusion chamber (shown in Fig. 5B) was constructed so that a "-900"-volt potential could be applied to the detector side with respect to the filter side. The detector was found to have an efficiency improvement of 25% as compared to one without electrostatic enhancement. It was considered that the alpha-containing aerosols inside the chamber, may have been subjected to plate-out on the plastic tube before they could reach the detector. In order to verify this, a new design was made in which the positive terminal was connected to the metal screen folded around the plastic cylinder. After irradiation in the radon box and processing, it was found that the efficiency increased about seven times, giving a sensitivity of 7.7 counts/day/pic (208 counts/day/Bq). This new version is expected to accumulate approximately 300 counts for one working month inside the uranium mine.

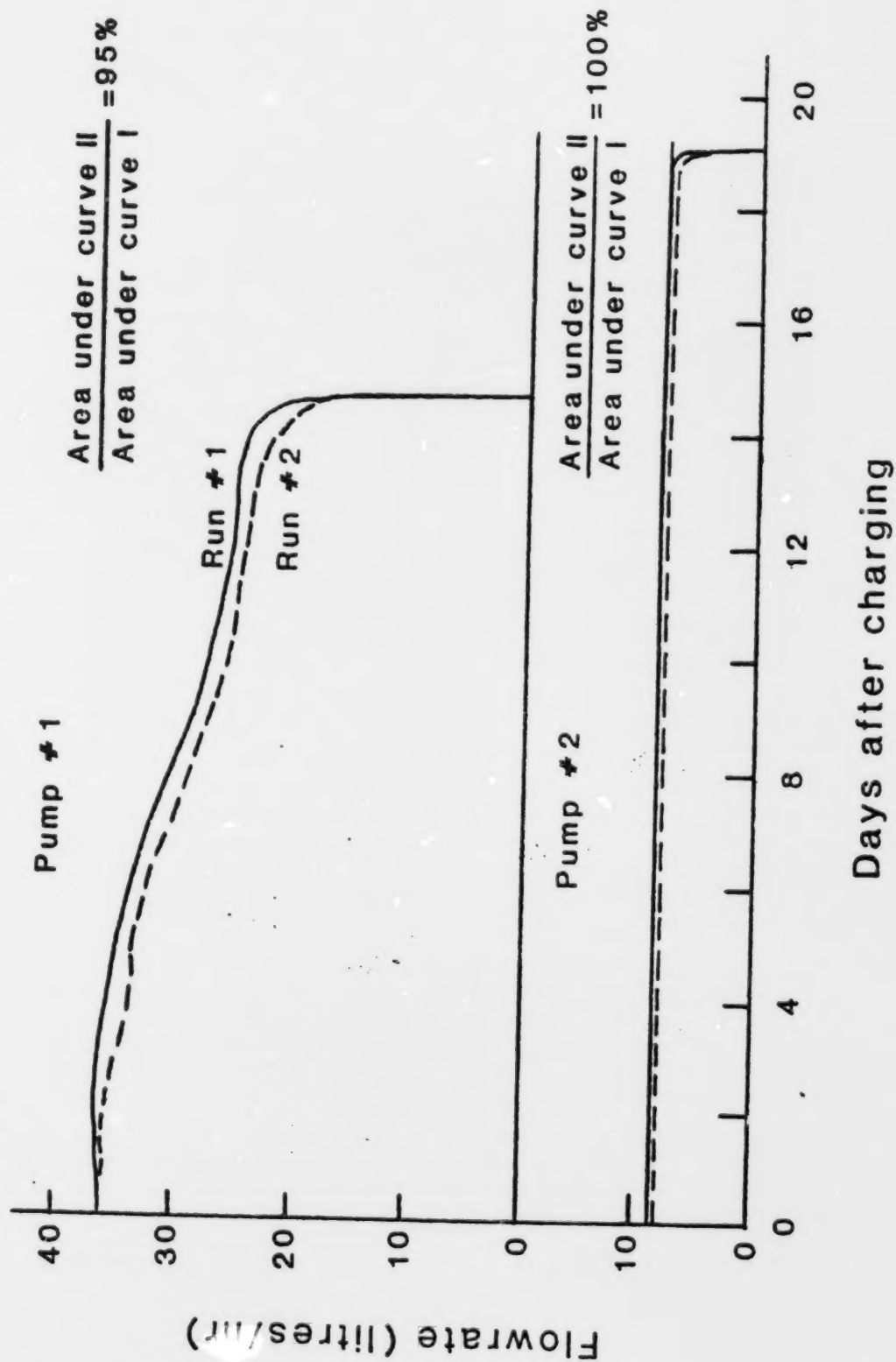


Fig. 4. Plot of flowrate versus days after charging.

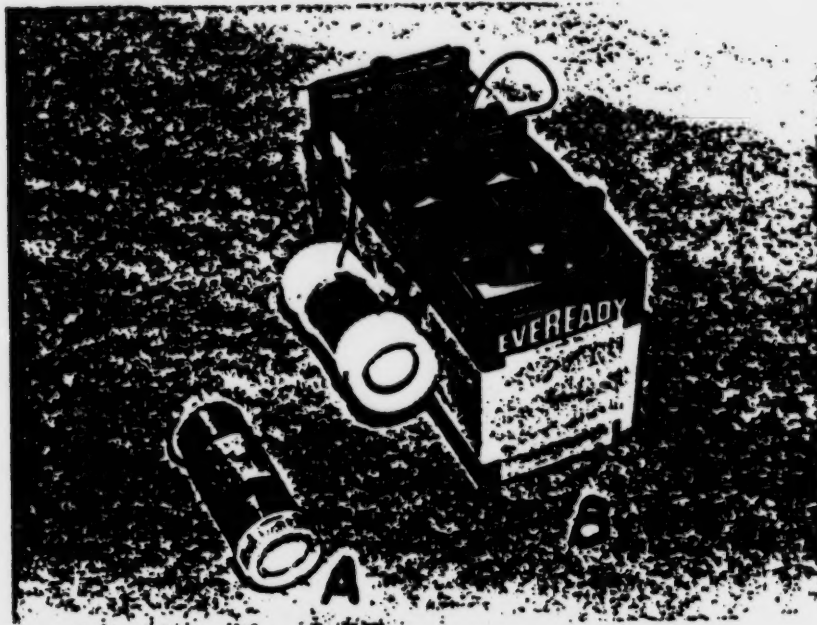


Fig. 5. The radon diffusion chamber

It will be shown later that the results of electrostatic enhancement are sufficiently encouraging to clearly indicate that the plane source method should be concentrated upon in this project. For this reason, further work on the RDC was suspended. The remaining work, originally planned for the RDC, was as follows:

1. The length of the radon diffusion chamber is 6 cm. Another version of 2.5 cm length was planned which would have been more convenient to use as a personal dosimeter. According to Benton, there would be no significant change in efficiency. The reason why the 6 cm length was first used is simply that the 6 cm tube is readily available in our shop.
2. Based upon the experience obtained from a passive radon monitor that uses a TLD as a detector, humidity should be controlled. The same practice may be necessary for the track-etch device. A drying agent may have had to be considered.
3. The required electrostatic potential may have been supplied by a capacitor or electret device instead of a battery.

4.2 Instruments for Electret Charging

An electret is a dielectric material that preserves its polarization for a long time after the external electric field that has produced this polarization is removed, and which sets up an electrostatic field in the surrounding space (8).

The word "electret" is analogous to the word "magnet". An electret establishes an electric field for a long time in the same way as a permanent magnet sets up a continuous magnetic field. The English physicist O. Heaviside introduced in 1896 the term "electret" and studied some theoretical problems related to electrets. But it was only in 1921 that the Japanese researcher Mototaro Eguchi actually investigated the electrets. After this, the electrets became the subject of numerous experimental and theoretical studies and found an increasingly wider practical application.

The most common versions of the electret are "thermoelectrets" and "electroelectrets". Thermoelectrets are produced when a heated dielectric is cooled in an electric field. Electroelectrets are produced under the action of an electric field without heating the dielectric. Instruments for both methods have been set up for this project and are briefly described in the following sections.

4.2.1 Direct Charging Method (Electroelectrets)

The process of Chittaporn (9) was closely followed. Teflon film of 0.001" (25 μ m) thickness was used. The equipment is shown in Fig. 6. The film was sandwiched between the electrodes; the charging potential was 6000 volts. After charging (the usual charging time is ten minutes to 2 hours), electrode A was lifted up before the high voltage was switched off.

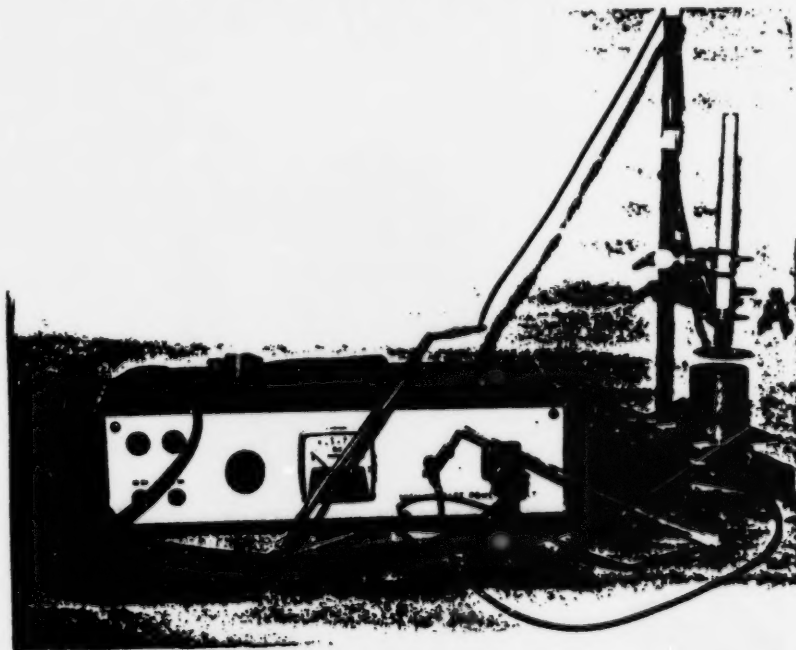


Fig. 6 Equipment for direct charging of electrets.

4.2.2 Oven Method (Thermoelectrets)

The process of Kotrappa⁽¹⁰⁾ was closely followed. Teflon film of 0.030" (0.76 mm) was used. The equipment is shown in Fig. 7.

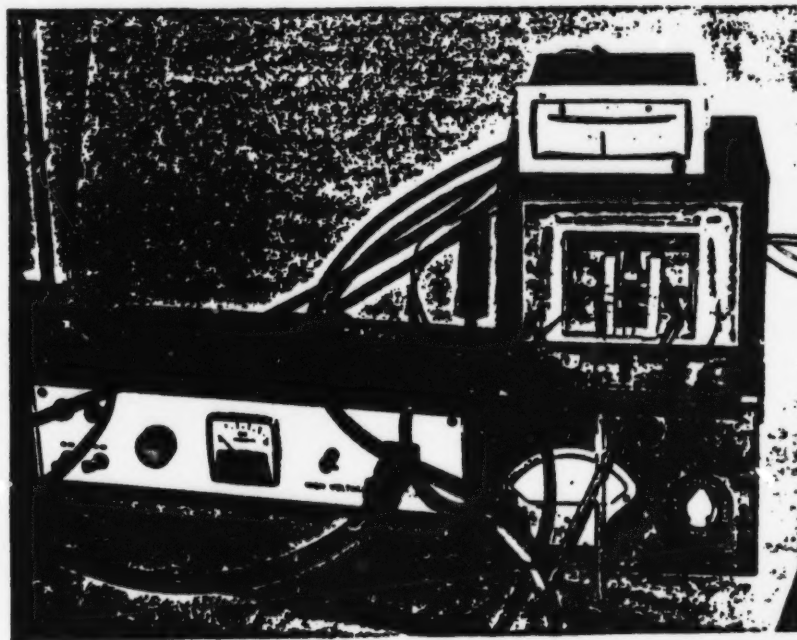


Fig. 7 Equipment for charging an electret by the oven method.

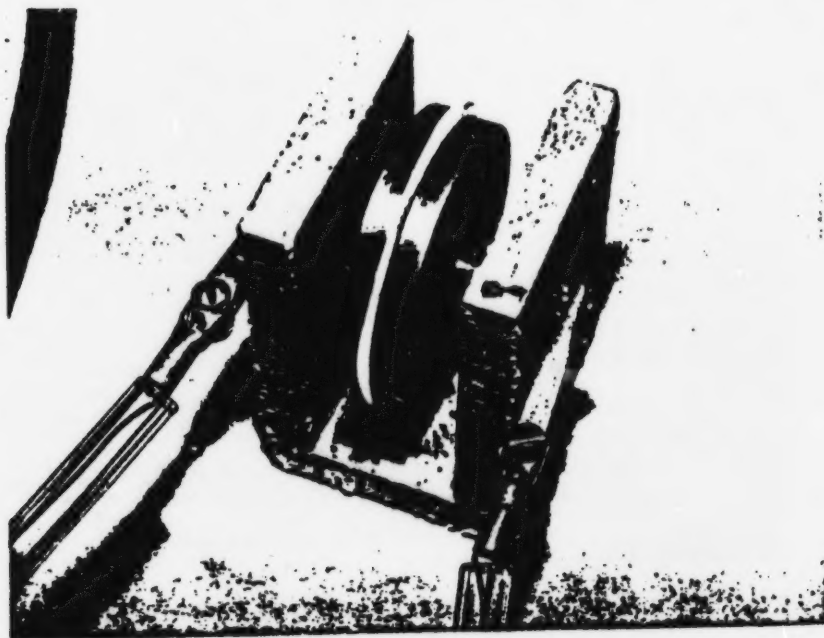


Fig. 8 Teflon film placed between electrodes.

The film was sandwiched between two polished electrodes, as shown in Fig. 8, and then placed inside the oven which was then heated to 400°F (close to the softening temperature of the substrate). A voltage of 6000 V was applied when the temperature reached 400°F. After eight hours, the oven was turned off but the high voltage was left on. The voltage was turned off only after the oven had cooled to room temperature.

4.3 Instruments for CR39 Calibration and Automatic Track Counting

4.3.1 Detector, Monoenergetic Alpha Source and Irradiation Facility

(1) CR39 Detector

CR39 sheets of 0.025" (0.64 mm) and 0.060" (1.5 mm) thickness were supplied by American Acrylics and Plastics, Inc. (25 Charles St., Stratford, Conn. 06497, U.S.A.). The sheets of 0.060" thickness were used in our work because it was found that they had less surface contamination than the 0.025" thick sheets.

(2) Monoenergetic Alpha Source

The source used was a USNBS Am-241 point source with an activity of 1.19×10^4 cps measured on March 1, 1978. Am-241 emits alpha particles of energies 5.49 MeV (65%) and 5.45 MeV (13%). In order to obtain alpha particles of appropriate energies for our tests, the alphas from Am-241 were subjected to degradation using polycarbonate absorbers of different thicknesses. The residual energies, as well as the spread, were measured using an alpha spectrometer. TABLE I gives the results of degradation.

TABLE I

Energy Degradation of Am-241 Alphas through Absorbers

Source	Peak Energy (MeV)	FWHM (MeV)	FW 1/10M* (MeV)
Am-241 (bare)	5.49	$\pm .02$	$\pm .02$
Am-241 (+15 μ m PC)	3.86	$\pm .11$	$\pm .20$
Am-241 (+20 μ m PC)	3.16	$\pm .16$	$\pm .33$
Am-241 (+20 μ m mylar)	2.13	$\pm .15$	$\pm .28$
(+5 μ m PC)			
Am-241 (+20 μ m mylar)	0.98	$\pm .24$	$\pm .51$
(+10 μ m PC)			

* The width of the energy peak measured at 1/10th of the maximum count level.

(3) Irradiation Facilities

Two irradiation facilities were constructed. The first facility (shown in Fig. 9) is continuously adjustable for different angles of alpha particle incidence but can accommodate only one detector at each irradiation. The second facility (shown in Fig. 10) allows an array of detectors to register alphas incident at 0°, 30°, 45° and 60° to the perpendicular during one irradiation. Both chambers were evacuated to eliminate energy degradation due to an air path. The irradiation facilities were checked using Kodak pathe' LR115 type II detector, because tracks in this detector of alphas of fixed energy at different angles of incidence (part of which is reproduced in Fig. 1) are well known from the 1979 NRC calibration.

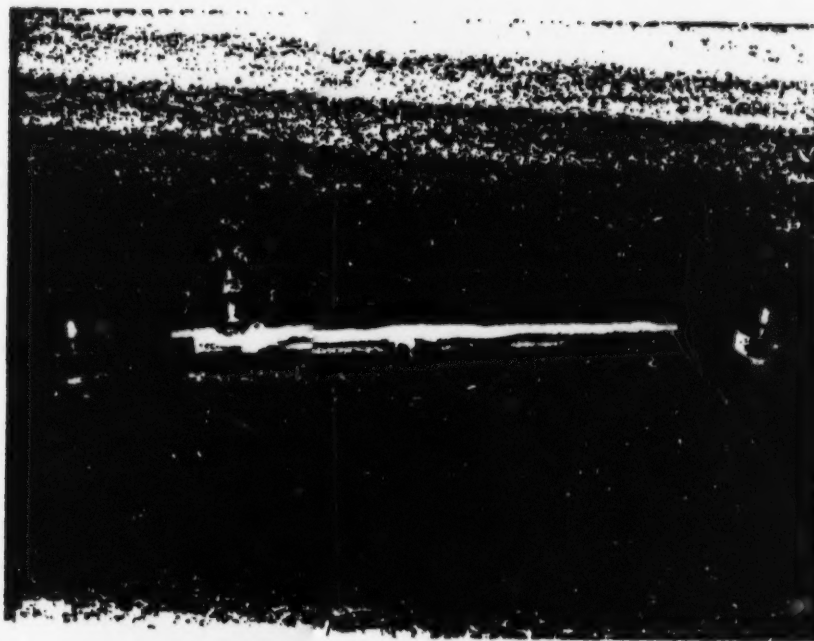


Fig. 9 (a) Irradiation facility #1.

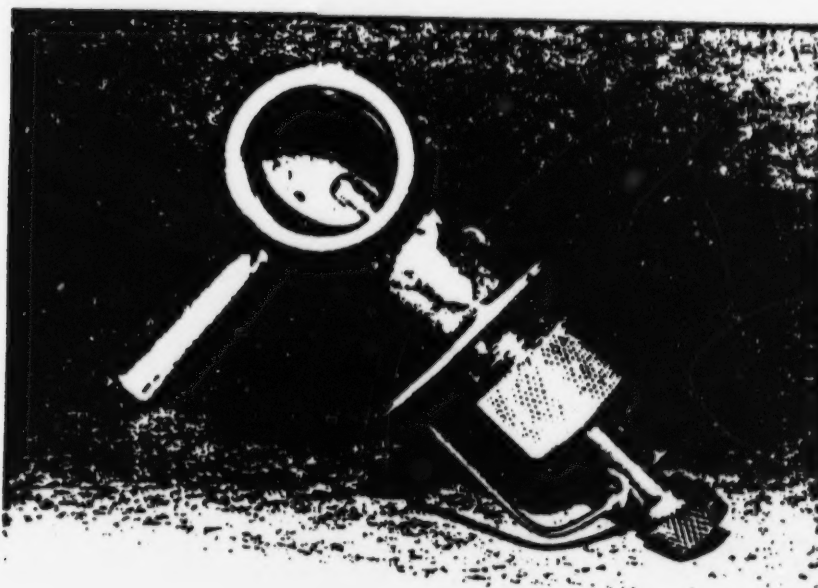


Fig. 9 (b) Close-up view of irradiation facility #1. - 16 -

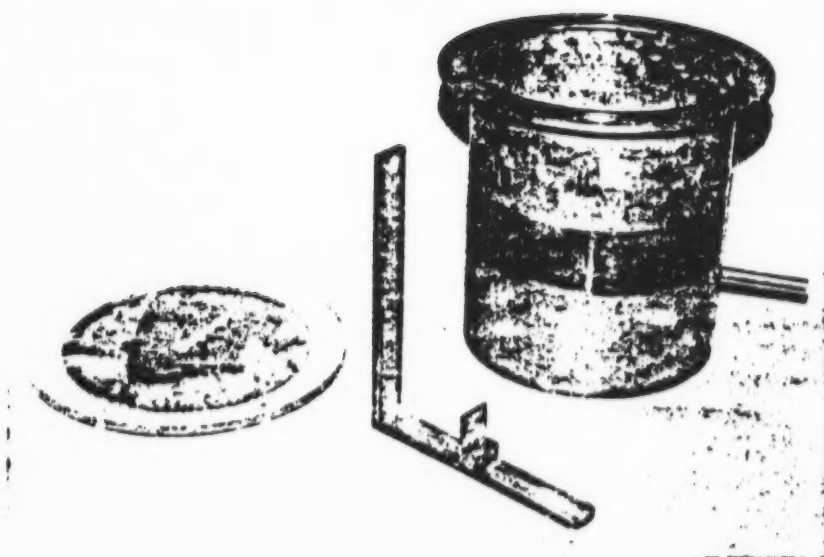


Fig. 10. Irradiation facility #2.

4.3.2 Automatic Counting Using Artek Counter #982

Recently, a commercially-available automatic counter, (Artek System Corporation, Farmingdale, New York, Model 982), designed for bacteriological work has been tested as a means of automatic counting of alpha particle tracks in the etched nitrocellulose film (LR115 type II). The system consists of a television camera coupled to a monocular microscope, the signal from the camera being fed directly to the electronic counter and monitored by a video display.

The principle of operation of the automatic counting system is the detection of changes in contrast on the scanned lines that form the raster pattern of a standard TV image. A dark (light) object in a light (dark) background is detected by sensing the contrast changes at the beginning and end of the object as the line of the image is scanned. This information not only detects the presence of an object but provides the automatic system with an appreciation of its size. The objective is achieved by comparing the information from one line scan with the information from the previous line scan. A vertical coincidence in two adjacent line scans tells the system that the same object is being scanned; on the other hand, a gap of at least one line between two vertically coincident small objects is required so that the system will recognize them as being separate.

The result of the automatic counting is controlled by four parameters - sensitivity and size adjustment controls on the Artek counter and the light intensity and the focus controls on the microscope. Using a standard etched LR115 type II detector with a known number of tracks (usually verified by manual counting), optimized settings of the sensitivity, size and light intensity can be obtained. Without altering the optimized settings, a push-button read-out of the total tracks on any etched LR115 type II samples can be obtained with only a slight adjustment of the focus being required between detector changes.

4.4 Instruments for Determining Electrostatic Enhancement and Alpha Particle Differentiation

In order to verify the efficiency of electrostatic enhancement and the capability of using the total absorption method for differentiating RaC' and ThC', a simulator that utilizes a capacitor was designed.

4.4.1 Simulator Design

Fig. 11a is a close-up view of a simulator. A is a piece of 18 μ M aluminized mylar (equivalent to 20 μ M polycarbonate film) which will be negatively charged by a charged capacitor placed in a cylindrical container D below the detector E. B is a piece of 40 μ M polycarbonate film which would stop alphas from RaC' but allow the detection of alphas from ThC'. C is a piece of 20 μ M polycarbonate absorber which would allow the detection of both ThC' and RaC'. The line marking the change of the thickness of the two absorbers can be identified in Figure 11a. Fig. 11b is a picture of the complete simulators and a charging device. The two simulators in position F are charged and the two in position G are not. I is the ground connection which is connected to the positive terminal. Charging is performed after the whole unit is placed in the radon box.

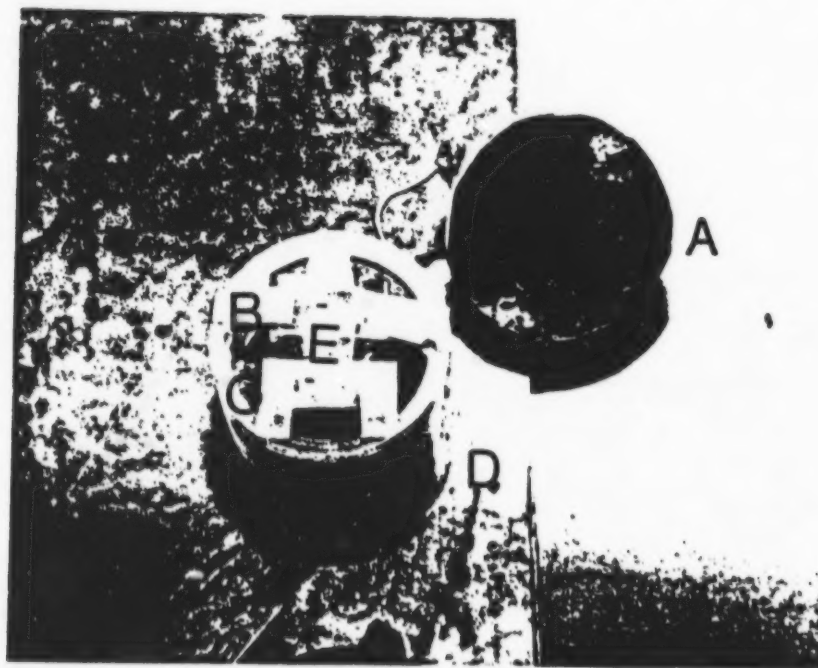


Fig. 11a A simulator.

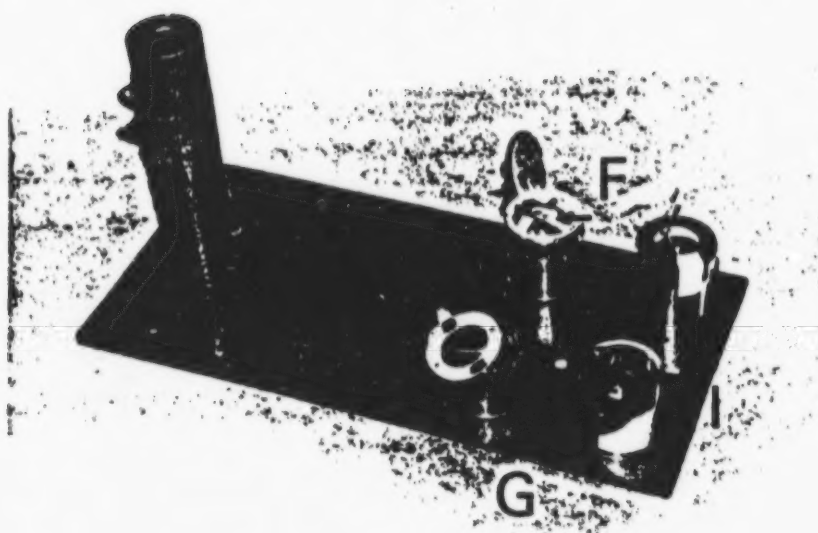


Fig. 11b Simulator and charging device.

4.4.2 Discharge Curve of a Capacitor

The curve shown in Fig. 12 was prepared with a simulator stored in a radon box at nearly 0% humidity.

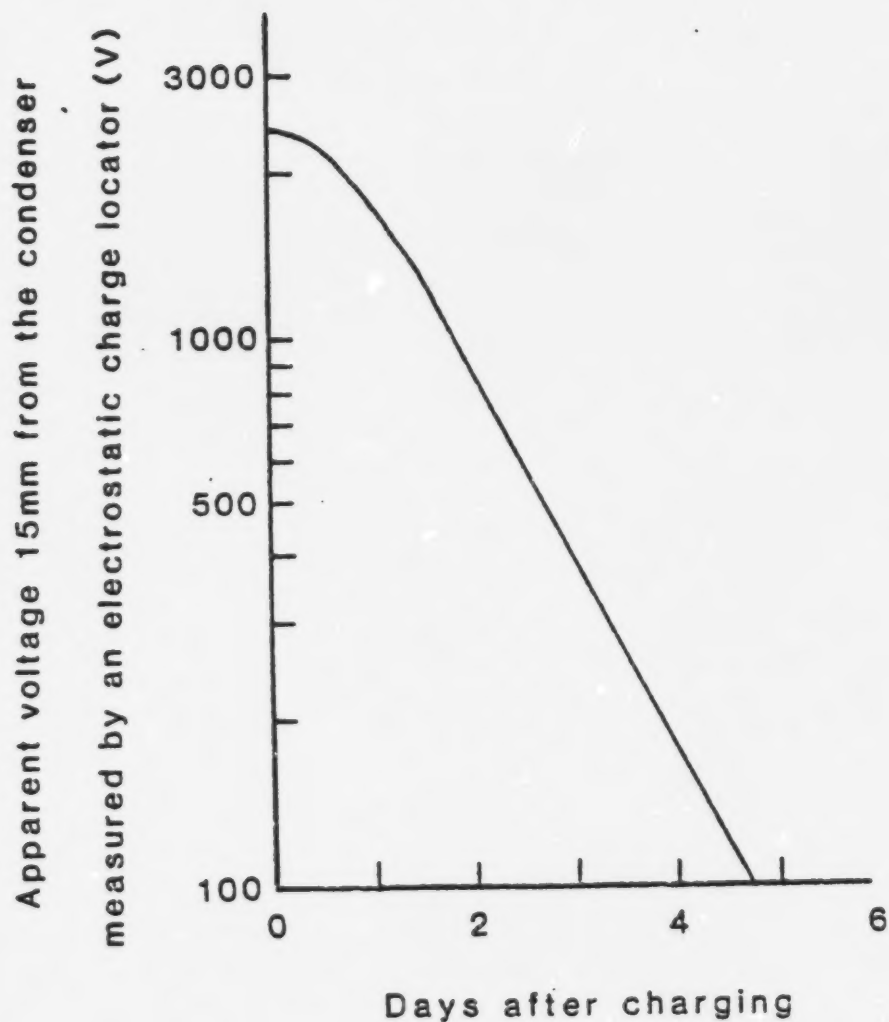
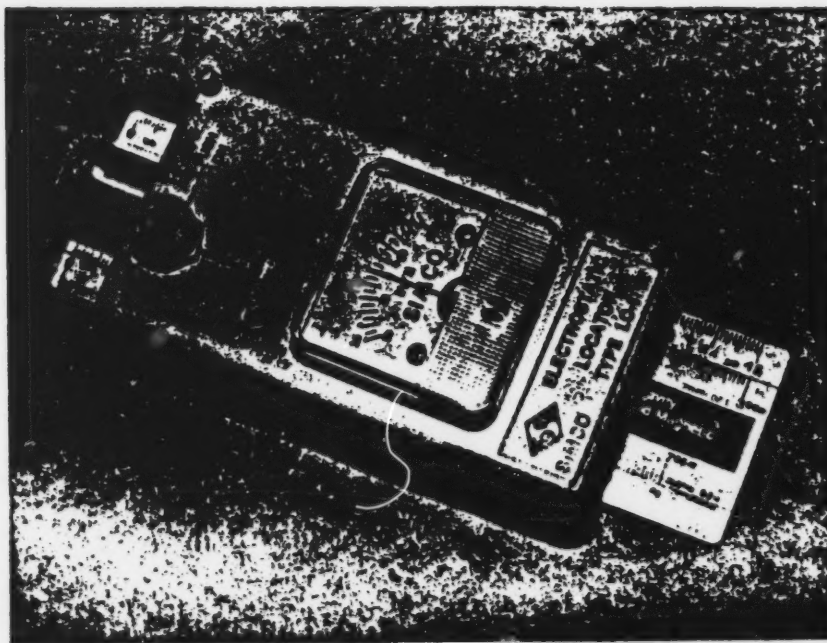
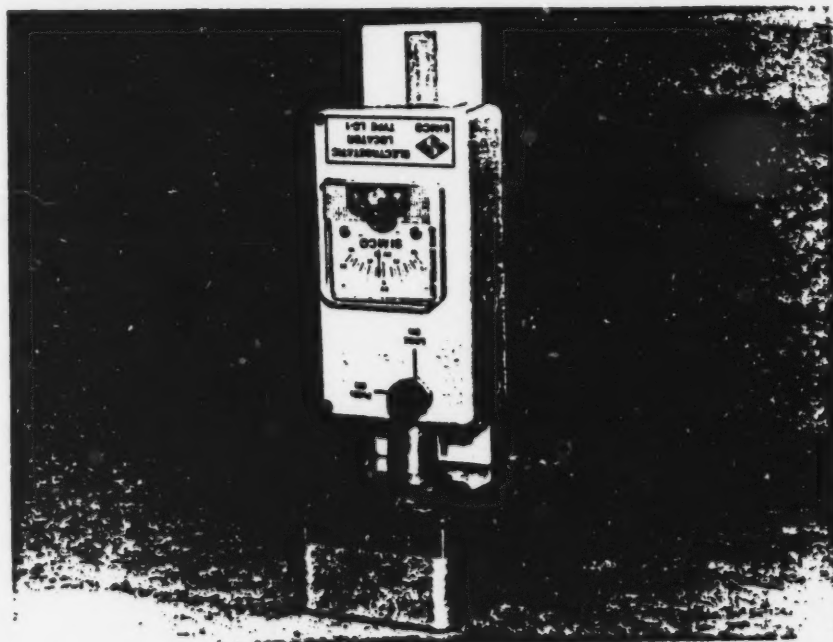


Fig. 12. Discharge curve of a capacitor.

The apparent voltage was measured by an electrostatic charge locator (Fig. 13a) at a fixed distance of 1.5 cm from the surface of the charged aluminized mylar (Fig. 13b).



13(a)



13(b)

Fig. 13(a) An electrostatic charge locator.
13(b) Placed at a fixed distance from the detector.

From the discharge curve shown in Fig. 12, it can be seen that, for an irradiation of a few hours, discharge need not be considered. However, for long term irradiations, some intermediate field-charging device should be considered.

4.5 Instruments for the Mine Test

Twelve prototypes of two different designs were constructed, (eight using capacitors, four using commercial electrets).

4.5.1 Description of the Prototype Capacitor-Type Dosimeter

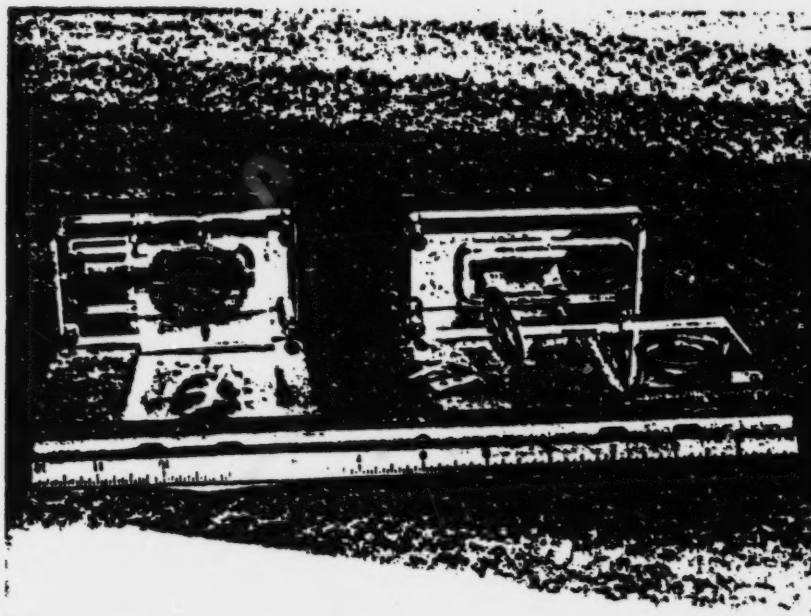


Fig. 14. Capacitor-type dosimeter.

The capacitor used in this prototype is the same as that in the simulator (with the absorber system), except that three safety precautions are incorporated (Fig. 15):

- a) a deeply recessed charging contact
- b) a protective insulating screen installed above the detecting window to prevent accidental discharge of the high voltage aluminized mylar film.
- c) the use of a high resistance chain between the capacitor and the detector window, to limit to a very low level the current that can be drawn from the capacitor.

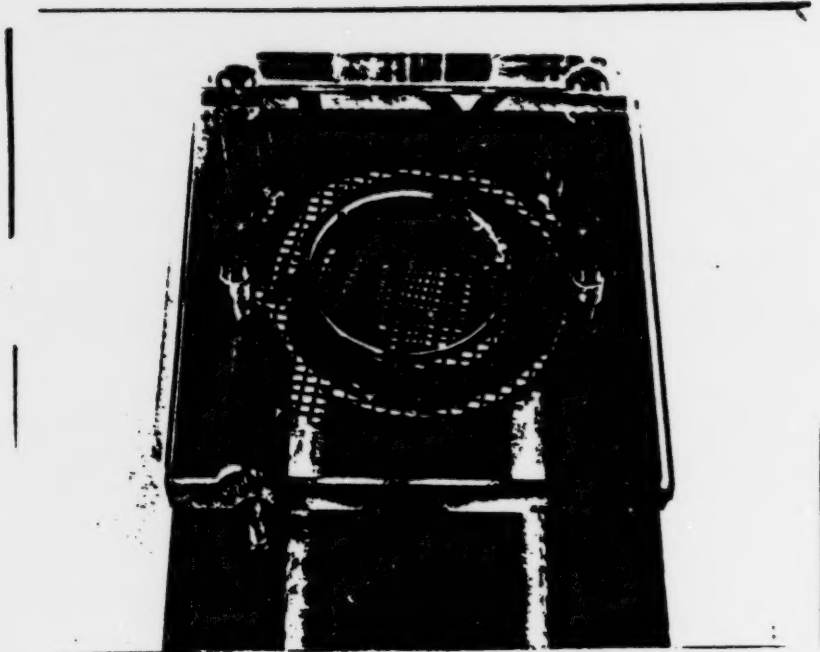


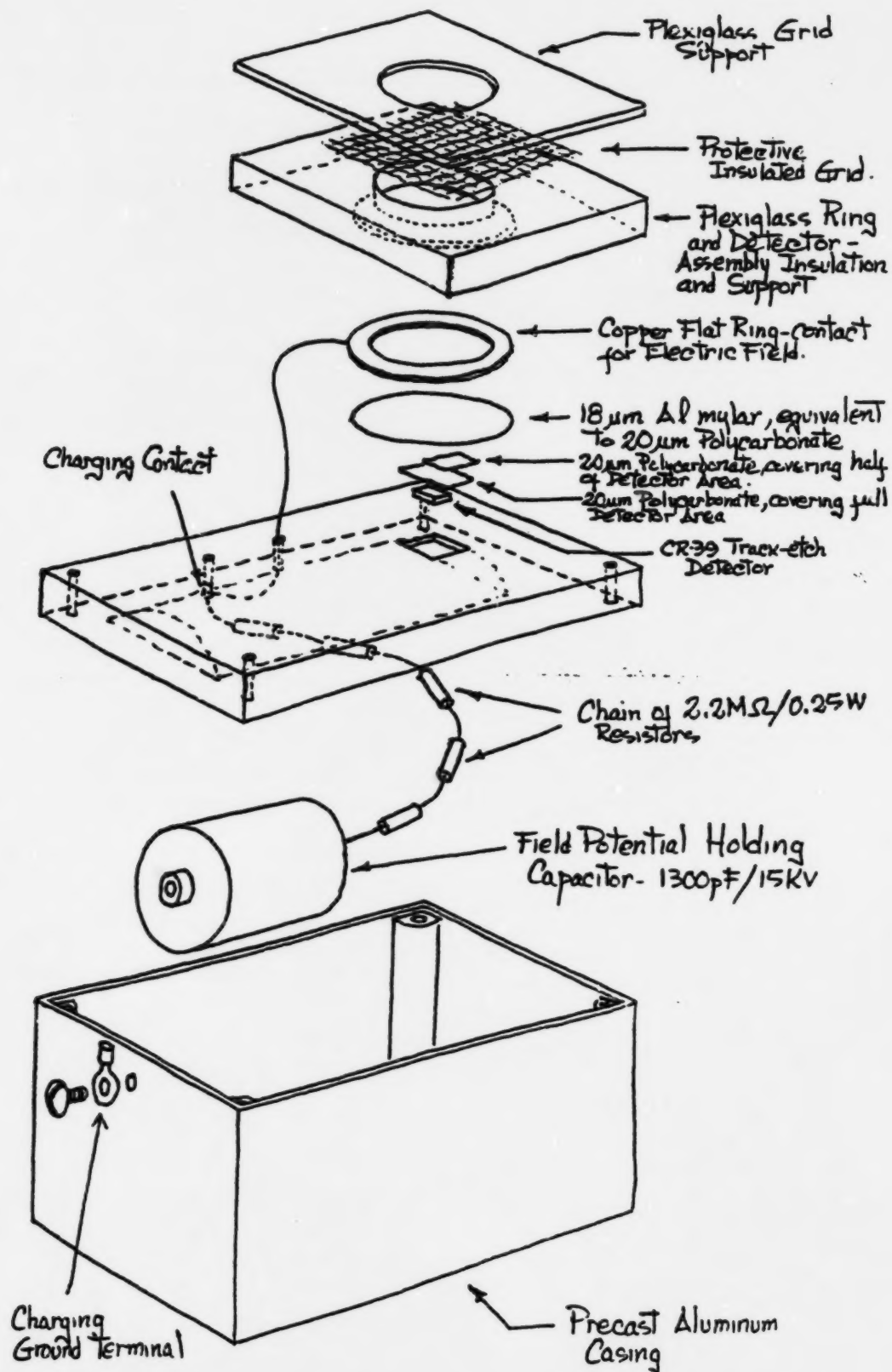
Fig. 15. Capacitor-type dosimeter showing safety guard.

This prototype (measuring 3.8 cm x 12.7 cm x 5.1 cm) is twice as large as the simulator. The larger volume was designed to allow the space for the continuous charging device discussed in Section 6.

4.5.2 Description of the Charger

As mentioned in Section 4.4.2, the field charger unit should be designed to keep the capacitor operating at the same voltage for more than a day. The field charger (Fig. 16) was constructed by modifying a commercially-available surveymeter obtained from an electronic budget store.

CAPACITOR TYPE PERSONAL DOSIMETER



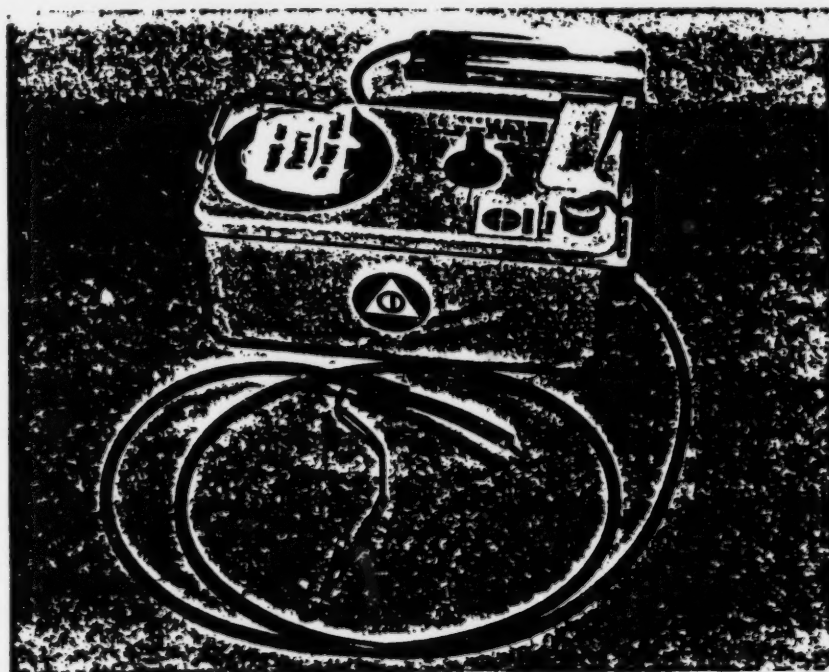


Fig. 16. A field charger.

Upon switching on, the terminal develops a negative potential of approximately 2,000 volts. Fig. 17 shows the charging operation. Complete charging can be performed by maintaining contact for fifteen seconds.

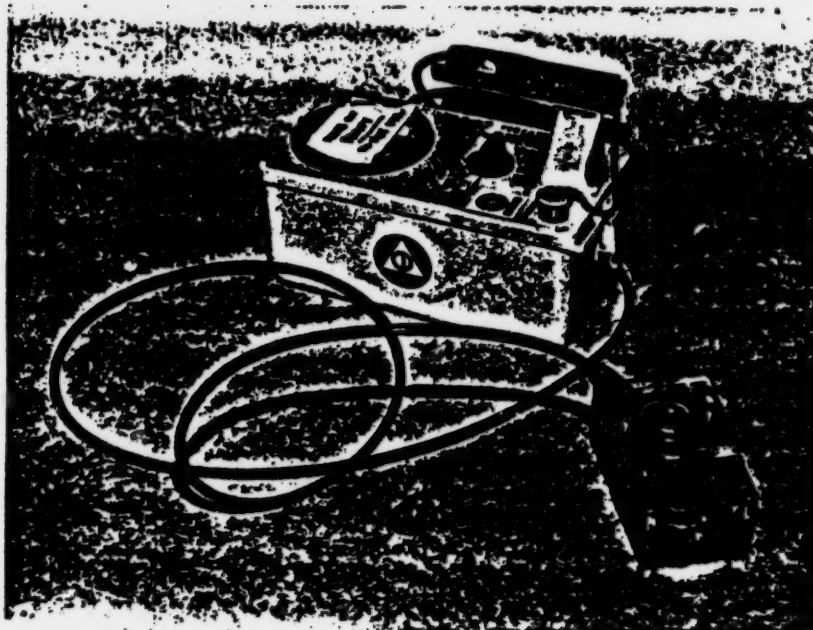


Fig. 17. Charging the capacitor-type dosimeter.

The charged condition of the prototypes was determined by measuring the apparent voltage with a Simcoe locator placed 1.5 cm from the protective insulating screen. A reading of 2.25 kV indicated that the unit was fully charged. The value of 2.25 kV was obtained by calibration using a DC voltage supply unit (Canberra HV power supply M3102).

4.5.3 Description of the Prototype Electret-type Dosimeters

The CR39 detector is surrounded by six commercial electrets of 1 cm diameter. The detector is completely wrapped with a polycarbonate film of 30 μm thickness; the overall shielding is provided by a film of 10 μm polycarbonate. On one-half of the wrapped detector, a layer of 20 μm polybarbonate is placed. This half, having an overall thickness of 60 μm , is the ThC' window. The other half, (overall thickness 40 μm) allows the detection of both ThC' and RaC'.

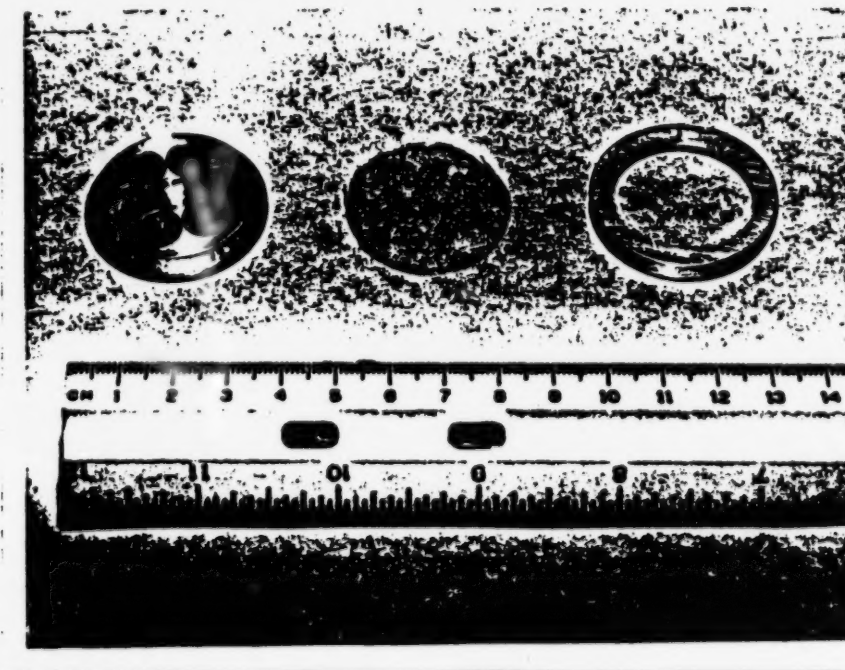


Fig. 18. Electret-type dosimeter.

ELECTRET TYPE PERSONAL DOSIMETER



5. EXPERIMENTAL RESULTS AND DISCUSSION

Using the instruments described above, experimental results were accumulated, and are listed according to the following sequence:

- (1) Calibration of CR39 and automatic counting
- (2) Capacitor electrostatic enhancement and differentiation of RaC' and ThC'
- (3) Electrostatic enhancement
- (4) Mine test

5.1 Calibration of CR39 and Automatic Counting

5.1.1 Calibration of CR39

- (1) Etching Conditions

The trial etching conditions (6.25 M NaOH at 75°C) follow the method of Fews and Henshaw of the University of Bristol, U.K. (11). According to their report, 5 MeV alpha tracks are etched just beyond the end of their ranges under these conditions.

- (2) Compilation of Standard Tracks

Standard tracks were prepared for alpha energies of 0.98, 2.13, 3.16, 3.9 and 5.6 MeV at incident angles of 0°, 30°, 45° and 60° from the perpendicular after etching for two, four and six hours in 6.25 M NaOH at 75°C. Altogether, forty pictures were printed from the photo negatives (245 magnification). These are shown as Figs. 19 - 58.

On the following pages - page 29 to page 42 - Fig. 19 to 58 showing standard tracks. The label for each figure reads:

Fig. W. Tracks of X-MeV alphas at an incident angle of Y on CR39 etched for Z hours.

Where W is the figure number
X is the alpha energy
Y is the incident angle
Z is the etching time

These pictures are of value for setting up the experimental design for the differentiation of alpha emitters according to the energy of their alpha particles.

The primary conclusions obtained from these results are summarized as follows:

1. Under these etching conditions, the maximum value of the track yield (more exactly, the yield of identifiable tracks for all energies and at all angles) is obtained after two hours of etching.
2. For 1 MeV alpha energy, only 0° alpha tracks exist. All oblique tracks were washed out during etching. For 2 MeV alpha energy, 0° and 30° alpha tracks exist, for 3 MeV alpha energy 0° , 30° and 45° alpha tracks exist. For alpha energies greater than 4 MeV, 0° to 60° alpha tracks are obtained. For 4 MeV alpha energy, however, the 60° alpha tracks were washed out after six hours of etching.
3. The efficiency of track registration is the same for all incident angles up to 55° . This is in agreement with the results obtained in CRNL(12).
4. The shape of the tracks is very similar to that predicted by the Bristol Group modelling(11).
5. The optimum etching conditions for differentiating ThC' from RaC' using 40 μ m and 60 μ m absorbers, are two hours of etching in 6.25 M NaOH at 75°C .

W

X Y Z

19

1 0 2

20

1 0 4

21

1 0 5

W

X Y Z

22

2 0 2

23

2 n 4

24

2 0 6

W

X Y Z

25

2 30 2

26

2 30 4

27

2 30 6

W

28

X Y Z

3 0 2

29

3 0 4

30

3 0 6

W

X Y Z

31

3 30 2

32

3 30 4

33

3 30 6

W

X Y Z

34

3 45 2

35

3 45 4

36

3 45 5

34

W

X Y Z

37

4 0 2

38

4 0 4

39

4 0 6

W

X Y Z

40

4 30 2

41

4 30 4

42

4 30 6

W

X Y Z

43

4 45 2

44

4 45 1

45

4 45 5

W

X Y Z

46

4 50 4

47

4 50 5

W

48

X Y Z

5 0 2

49

5 0 4

50

5 0 6

W

X Y Z

51

5 30 2

52

5 30 4

53

5 30 5

W

X Y Z

54

5 45 2

55

5 45 4

56

5 45 6

W

X Y Z

57

5 60 2

58

5 60 2

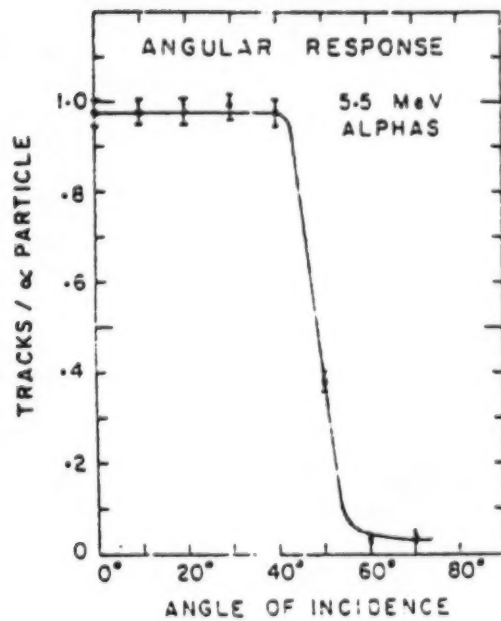


Fig. 59. Efficiency of track registration versus incident angles. (12).

5.1.2 Automatic Counting Using Artek Counter 982

The results presented in Section 5.1.1 (2) were obtained by manual read-out with a microscope, with specified magnifying power, light illumination and optical absorber. Of the three settings mentioned, the magnifying power is the most important. As an example, if the nitrocellulose detector (Kodak LR115 type II) is used to differentiate ThC' alphas from RaC' alphas, a lower power is needed (e.g. 40X) because at low power, the tracks of ThC' alphas will appear as non-transparent spots to the human eye. If high power is used (e.g. 200X), some of the tracks of the ThC' alphas will appear to be transparent. Although the situation is not the same with CR39, optimal power should be chosen based upon the simplicity of track counting. That is, a higher power may not cause any problems for CR39 in the alpha emitter differentiation, but higher power requires that more optical fields be counted in order to get the same counting statistics. The optimum magnification adopted for the counting of tracks in CR39 is 100X.

With manual counting optimized, the next step was to determine whether the standard image analyzer (Artek 982), which had already been used successfully with LR115 type II, could be used with CR39. This is the main interest of this project because the tracks registered on the CR39 in passive dosimeters are those of alphas of different energies, impinging on the detector at different angles of incidence.

The test was conducted using a sample with very high track density. By comparing the manual counting results with those obtained using the automatic counter at a microscope magnification of 10X*, it was found that there was a track loss of 25% with the automatic counter. The loss was caused by the overlapping of tracks. By changing the microscope magnifying power to 20X, there was no loss of counts by the automatic counter. There seems to be a correlation between the track density and the minimum magnifying power at which there is no significant loss of counts. To verify this assumption, several samples of CR39 were irradiated for different times, etched and then counted, using the automatic counter. The results are shown in Fig. 60.

The graph indicates that, if the track density is no higher than $300 \times 10^3/\text{cm}^2$, the automatic counter can be used with the microscope at a magnifying power of 10X.

By fixing the microscope light intensity at 7, the magnifying power at 10X, the sensitivity level of the counter at 2.38 (arbitrary scale) and size control at minimum, automatic counting of the CR39 passive monitor was found to have a precision within 12% of the manual counting figure. The track densities of the samples counted in Table II are all below 300×10^3 tracks/cm² so a magnifying power of 10 can be used.

* For manual counting, overall magnifying power is the product of that of the objective lens (usually 10X) and the eyepiece (usually 10X also). For automatic counting, the eyepiece is removed so only the magnifying power of the objective is relevant (10X).

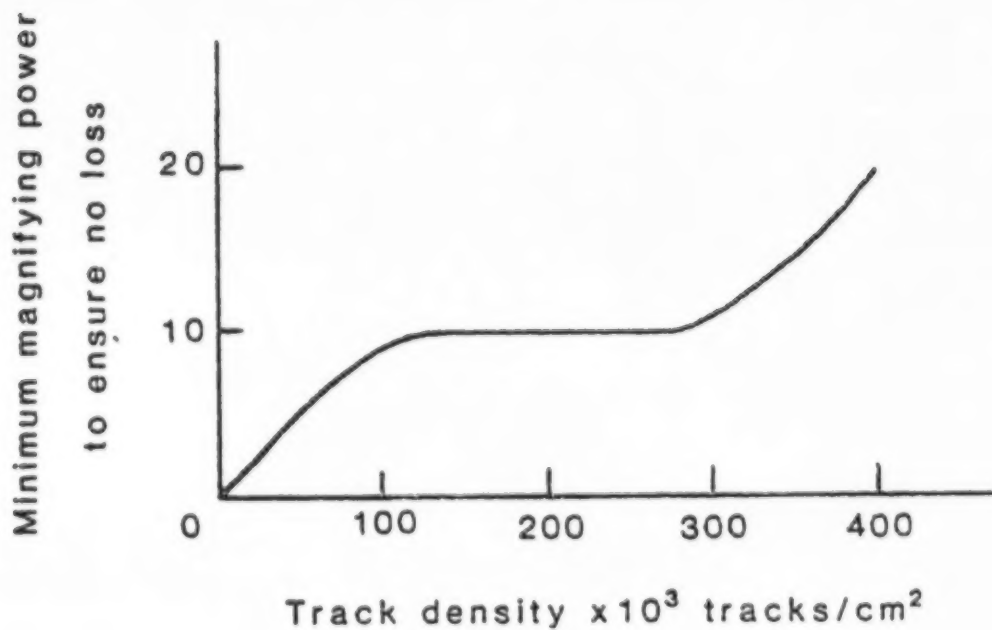


Fig. 60. Graph showing the optimum magnifying power for different track densities.

TABLE II

Comparison of Manual and Automatic Read-out

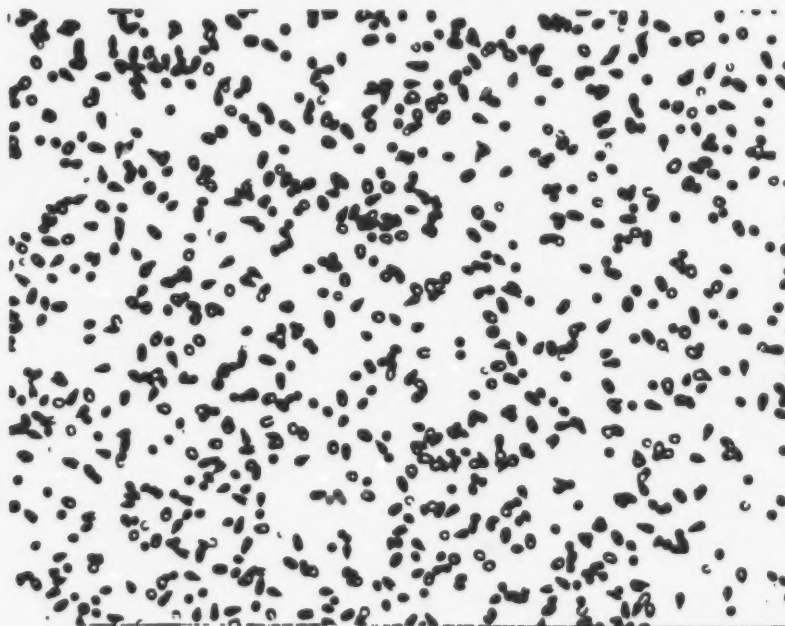
	Manual	Automatic	$\left[\frac{\text{Manual} - \text{Automatic}}{\text{Manual}} \right] \times 100 \%$
1	72	64	11
2	121	135	12
3	99	91	8
4	190	199	5
5	256	269	5
6	204	202	1
7	238	239	1
8	645	650	<1
9	842	843	<1
10	436	445	2
11	648	624	4
12	501	522	4
13	880	875	<1

5.2 Electrostatic Enhancement Using a Capacitor-type Simulator
and Differentiation of RaC' from ThC'

5.2.1 Efficiency Enhancement

Electrostatic enhancement is demonstrated by an experiment in which, after a three-day irradiation in a radon box (activity of ~ 2070 mBq/L), the detectors in an uncharged simulator and in a simulator charged to 4000 volts were processed. Figs. 61a and 61b show the difference in the number of tracks. It was found that there is no change in enhancement even if the voltage is lowered to 2800 volts.

Fig. 61a. Tracks in a detector of an uncharged simulator.



5.2.2 Differentiation of ThC' and RaC'

As previously mentioned, ThC' and RaC' were to be differentiated by using different thicknesses of absorbers. These tests were done in a radon (thoron) box using simulators. An active survey meter with LR115 type II detector was used as a reference.

(1) Test #1

Absorbers of polycarbonate film, of thicknesses 40 μm and 60 μm , were used. The 40 μm absorber allows the detection of both RaC' and ThC'; the 60 μm absorber, of ThC' only. (Refer to Table XVI.) The simulator was charged to 2000 volts and irradiated in the radon (thoron) box for six hours. After two hours of etching, the results are as shown in TABLE III.

TABLE III

Differentiation of ThC' and RaC' Using Absorbers
Test #1

Detectors	Total Number of Tracks per 0.28cm ² *		
	ThC'	ThC' + RaC'	$\frac{\text{ThC}'}{\text{ThC}' + \text{RaC}'}$
LR115 type II in active system 5 L/h	247	461	0.54
CR39 in simulator #1	154	345	0.45
CR39 in simulator #2	117	360	0.33
CR39 in simulator #3	77	227	0.34

* Standard CEA geometry of circular area with radius of 0.3 cm.

The above data show that the ratio ThC'/ThC' + RaC' for each of the three simulators is lower than that for the active system. Also, since the total number of ThC' and RaC' tracks includes some tracks of RaA (Refer to Section 6.1), the value of the ratio is actually even lower. This relatively low value is considered to be due to mainly the thickness of the ThC' window.

(2) Test #2

To verify the above assumption, the test was repeated with thinner ThC' windows. The results are tabulated in TABLE IV.

TABLE IV

Differentiation of ThC' and RaC' Using Absorbers

Test #2

Detectors	Total Number of Tracks per 0.28cm^2		
	ThC'	ThC' + RaC'	$\frac{\text{ThC}'}{\text{ThC}' + \text{RaC}'}$
LR115 Type II	165	264	0.62
Simulator #1 (55 μm)	72	121	0.60
Simulator #2 (55 μm)	68	99	0.69
Simulator #3 (50 μm)	190	256	0.74
Simulator #4 (50 μm)	204	238	0.86

Based on these results, it was tentatively concluded that:

1. The 55 μm absorber is preferable
2. The detector LR115 type II using the CEA method is assumed to separate completely RaA, RaC' and ThC' such that the ratio $\frac{\text{ThC}'}{\text{ThC}' + \text{RaC}'}$ so determined is absolute. Measurements obtained using CR39 however, will include some portion of RaA in the (ThC' + RaC') determination. According to the results of the ratio $\frac{\text{ThC}'}{\text{ThC}' + \text{RaC}'}$ determined by CR39 using 55 μm it does not show appreciable difference with that obtained by using the CEA device. Therefore, it is considered that the amount of RaA is insignificant.

5.3 Electrostatic Enhancement Using Electrets

5.3.1 Performance Test of the Charged Teflon (Electret)

Directly after charging, the teflon film, prepared by either the direct charging or the oven method, showed a surface potential of 2.5 kV, measured by a Simcoe electrostatic locator at a distance 1.5 cm from the charged surface.

The charged condition remained for a considerably longer period if the teflon was stored in a dust free environment. In the comparatively clean laboratory atmosphere ($\sim 5 \times 10^4$ particles/ml, $\sim 50\%$ humidity) the surface charge on the teflon lasted for more than a day. After one day, it degraded to an undetectable level, measuring less than 0.1 kV on the electrostatic locator scale. By carefully washing and drying the electret, the charge could be restored to about half of the original level.

In order to determine the efficiency enhancement that can be obtained in a short irradiation time, the charged teflon detector assembly along with capacitor-type simulators and a CEA survey meter were irradiated in the radon (thoron) box for six hours. TABLE V gives the track densities in the associated detectors counted after etching for two hours.

TABLE V

Results of the Performance Test of the Charged Teflon

System (All with Absorbers)	Track Density/ 0.28cm^2 / 6 hours	
	ThC'	RaC'
Simulator (no charge)	44	24
Simulator (2000 volts)	253	185
0.001" (25 μm) electret	135	72
0.030" (0.76 mm) electret	221	122
CEA survey meter	1330	460

The 0.001" (25 μm) electret showed an enhancement of three times; and the 0.030" (0.76 mm) electret, five times that of the uncharged simulator. The enhancement of the 0.030" electret seems to be of the same order as that of the simulator. Track density without electrostatic enhancement was of the order of 40 ± 15 .

5.3.2 Performance Test of the Commercial Electrets

The commercial electrets were obtained from miniature microphones⁽¹²⁾. The first two models used (Fig. 62) were M140, 1.6 cm OD and -M141, 1.0 cm OD.

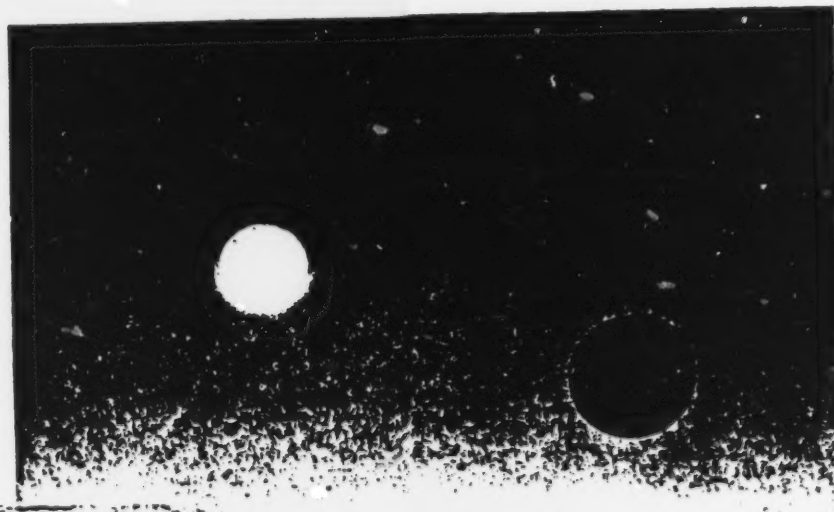


Fig. 62. Commercial electrets.

The following three tests were performed to verify the basic properties of commercial electrets:

(1) Test #1

The object of the test was to determine the effect of electret size on detection efficiency enhancement.

Two commercially available electrets were used, one with a diameter of 1 cm and another, 1.6 cm. The effective voltage measured using the Simcoe locator was 200 volts, about 1/10 of that for the charged simulator. Both electrets showed the same effective potential. To find out whether the electrets were sensitive to a dusty atmosphere, each electret was loaded with a CR39 detector on its upper surface and then irradiated in the radon(thoron) box for fifteen hours. One bare detector without an electret was also irradiated at the same time for comparison purposes. After irradiation, the three detectors were etched for two hours. TABLE VI gives the counting results.

TABLE VI

The Effect of Electret Size on Efficiency Enhancement

<u>System</u>	<u>Tracks/0.28cm² / 6 h</u>
Detector on 1.6 cm electret	291
Detector on 1 cm electret	206
Bare detector	134

After exposing for fifteen hours in the atmosphere of the radon (thoron) box, the effective voltage of the electrets seemed to be unchanged.

Conclusions: With a single commercial electret, the registration efficiency is approximately doubled; an electret of a larger area tends to be more efficient. Also, dust does not appear to affect the effective voltage of the commercial electrets (at least when initially charged to $\approx$ 200 volts).

(2) Test #2

The test was conducted to determine the effect of electret orientation on efficiency enhancement.

Two different orientations of electrets were tested. In one orientation, the detector was surrounded by 4 electrets and in another orientation, the detector was on top of 4 electrets stacked vertically. A simulator charged to 2000 volts was irradiated at the same time with the electrets. The time of irradiation was 6 hours and the etching time was 2 hours. The counting results are tabulated in TABLE VII.

TABLE VII

The Effect of Electret Orientation on Efficiency Enhancement

System (All with Absorbers)	Tracks/ 0.28cm^2 / 6 h	
	ThC'	RaC'
Simulator (no charge)	36	42
Detector with absorbers in simulator (2000 volts)	262	177
Four electrets surrounding detector	108	108
Detector on four stacked electrets	69	78

With four electrets surrounding the CR39 detector, the registration efficiency enhancement is three times that without electrets.

(3) Test #3

This test was performed to determine the effect of covering the electret with a $10\text{ }\mu\text{m}$ polycarbonate film and exposing it to a high radon atmosphere.

The test was conducted in a radon box with a radon level in excess of 1.85 Bq/L . Two electrets, one with a cover of $10\text{ }\mu\text{m}$ polycarbonate film and one without, and their associated detectors, were irradiated in a radon (thoron) box, along with a detector without an electret. Initially, the negative field of the electret was unaffected by the polycarbonate film, but after one hour, the negative field degraded and six hours later, the field became slightly positive. At the end of the irradiation, the negative field of the electret was restored upon removing the film cover. The uncovered electret was found to be damaged; after irradiation, there was no longer any indication of the negative field. Ultrasonic cleaning was effective in restoring the field, but the strong vibrations damaged the electret surface.

The electret-detector system with a cover of $10\text{ }\mu\text{m}$ polycarbonate film appeared to give an efficiency enhancement of three times that of a detector without an electret; the bare electret-detector system, two times. The results are shown in TABLE VIII.

TABLE VIII

The Effect of Covering the Electret on Efficiency Enhancement

System (All with Absorbers)	Tracks/ 0.28cm^2 / 6 h	
	ThC	RaC'
Detector and electret covered with $10\text{ }\mu\text{m}$ polycarbonate film	157	90
Detector and electret uncovered	99	55
Detector without electret	40	35

5.3.3 Simulation of a Mine Test - Efficiency Enhancement Using Negatively Charged Devices

The following were irradiated in the radon (thoron) box: a charged simulator an electret device with six electrets surrounding the CR39 detector and an active device that uses a CEA head connected to a 30 Lph pump. After etching, the track densities of the associated detectors were determined. The total number of tracks in the active system was divided by 6 in order to simulate the track yield expected using a pump with a flow rate of 6 Lph, the usual flow rate of a personal dosimeter. Compared with the active system, the simulator was found to have an efficiency of ~50% and the electret device, ~20%, for counting RaC' tracks and ~30% and ~13% respectively, for counting ThC' tracks.

TABLE IX

Results of the Simulated Mine Test

System	Tracks/0.28cm ² / 6 h	
	ThC'	RaC'
Simulator (1500 volts)	283	194
Electret device with six electrets surrounding the CR39 detector	137	85
CEA (normalized to 5 Lph)	1040	422

5.3.4 Conclusions on the Use of Electret Enhancement

- (1) An electret loses its surface charge after exposure to moisture or dust. A well charged electret should recover its charge after proper washing and drying. According to this criterion, neither the laboratory produced electret nor the commercial electret met the above recovery criterion.
- (2) Based upon our experience in electret charging, it is tentatively concluded that:
 - (a) the oven temperature should be above the plastic softening point;
 - (b) the oven should be extremely clean.

The above two points were confirmed with the electret charging group of the ANL, U.S.A. (Appendix B).
- (3) The fact that the charge of the electret is diminished by moisture and dust is a disadvantage if it is to be used in the mine. Although the charge can be restored after proper washing, this procedure would not be practical for use in the mine because the washing process needs to be conducted in a very careful way. The electret is successfully used in radon and other dosimetric applications where it is not in direct contact with the external air. For instance, radon is determined by detecting its decay products inside the radon diffusion chamber. The electret required for enhancement is mounted inside the chamber and need not be in contact with the external atmosphere.

- (4) The dust and humidity problems arising from operation in the mine atmosphere can be solved by covering the electret with a dielectric sheet however. Careful design is needed to retain the induced negative charge on the dielectric sheet. It is suggested that some other method of electrostatic enhancement, for instance, the capacitor, be tested along with the electret.

5.4 Mine Test Results

The mine test was carried out to determine:

1. Whether the ratio ThC'/RaC' , within a limited area in the mine, can be assumed to be constant.

If the ratio is constant, then the absolute efficiency of counting ThC' and RaC' in the atmosphere can be obtained with reference to the respective counts recorded by an active dosimeter located in the same area.

2. The accuracy with which measurements can be made, the extent to which factors influencing the spread can be minimized. (The standard deviation so far achieved by the current passive system, as reported by Domanski, is 30%.)

Prototype dosimeters using capacitors and using commercial electrets were tested in the mines in the Elliot Lake region.

5.4.1 Preliminary Laboratory Tests

Before the mine test, radon (thoron) box tests were conducted in order to check the performance of the prototypes.

(1) Test #1 (Capacitor-type Dosimeters)

Four prototypes (Nos. 5, 6, 7 and 8) were irradiated for 5½ hours after charging them with a field charger. The initial reading for each dosimeter, measured with a Simcoe charge locator, was 2.25 kV falling to 0.75 kV at the end of the test period. TABLE X gives the track density results.

TABLE X

Determination of ThC'/RaC' Ratio Using the Prototype Dosimeters
Results of Laboratory Test #1

	<u>No. 5</u>	<u>No. 6</u>	<u>No. 7</u>	<u>No. 8</u>	<u>Average</u>
ThC'	264	276	292	146	$244.5 \pm 17\%$
RaC'	536	596	720	300	$538.0 \pm 19\%$
ThC'/RaC'	0.49	0.46	0.41	0.49	$0.46 \pm 3\%$

All four prototypes show the same ThC'/RaC' ratio. The standard deviation of the track densities is around 18%. In order to determine the reason for the deviation, test #2 was conducted.

(2) Test #2

Test #2 was conducted using a stable mains powered high voltage supply. The same four prototypes were used, connected in parallel to a DC supply of 1500 volts and irradiated in the radon (thoron) box for four hours. The charge potential measured on each dosimeter was 2.25 kV.

In order to investigate the effect of the geometry of the detector assembly on the standard deviation of the track density, two detectors, one above the other, were installed under the aluminized mylar film prototype No. 6. Only a ThC' window was used for this test. The lower detector was on the same plane as the detectors in the other prototypes; the upper detector was "displaced". Any difference in the track density of this upper detector would indicate the effect of a detector displacement of approximately 1.5 mm (corresponding to the detector thickness). TABLE XI gives the track density values.

TABLE XI

Determination of ThC'/RaC' Ratio Using the Prototype Dosimeters
Results of Laboratory Test #2

	<u>No. 5</u>	<u>No. 6</u>	<u>No. 7</u>	<u>No. 8</u>	<u>Average</u>
ThC'	115	Lower 112 Upper 224	103	60	$91 \pm 16\%$
RaC'	297		241	165	$234 \pm 17\%$
ThC'/RaC'	0.37		0.43	0.36	$0.39 \pm 7\%$

Again the ThC'/RaC' ratio appears to be the same. The standard deviation of the track densities is the same as in Test #1. This indicates that the deviation contributed by the field charger is not a major factor. The values of the ThC' track in prototype No. 6 indicate that the geometry of the detector assembly is a significant factor influencing the spread in results; therefore, the geometry should be precise and reproducible.

5.4.2 Mine Test

(1) General Description

The absorber for ThC' used in the dosimeters for the mine test was 60 μ m thick. Although an earlier study (Section 5.2.2 (2)) showed that a 55 μ m absorber gave better results, a 55 μ m thick polycarbonate film was not available. If several layers of film had been added to make up this thickness (30 μ m film to wrap the detector, 10 μ m film for overall shielding and three 5 μ m layers to make 55 μ m) additional uncertainties would have been introduced.

Two sets of dosimeters were irradiated in the mine. Each set consisted of one battery-operated pump with a CEA detecting head, four capacitor-type passive dosimeters and two electret-type passive dosimeters. The only difference between the two sets was that the active unit of set A was operated at 36 L/h and that of set B, at 10 L/h. Each set was enclosed in a cylindrical mesh screen approximately one meter in diameter. The distance between the two sets was approximately thirty meters. Both sets were irradiated for five days (120 h), from August 12 to August 17, 1983.

The capacitor type dosimeters were re-charged after three days using the portable field charger. Kusnetz measurements using a Trimet counter were also made at the start, on the day of re-charging, and at the end of irradiation.

The flow rate of the battery-operated pump was checked at the start and at the end of irradiation and was found to be unchanged. The following tables give the Kusnetz (TABLE XII) and the time average results (TABLE XIII).

TABLE XII

Kusnetz Measurement Results

Date	WL at Set A	WL at Set B
August 12	0.17	0.13
August 15	0.26	0.21
August 17	0.13	0.16
Average	0.19	0.17

TABLE XIII

WL Results from Time Average Survey Meters

	<u>Flow Rate</u>	<u>RaA</u>	<u>RaC'</u>	<u>ThC'</u>	<u>WL Radon</u>	<u>WL Thoron</u>
Set A	36 L/h $\pm$ 5%	12965	15483	14195	0.20	0.21
Set B	10 L/h $\pm$ 5%	3706	4538	3634	0.21	0.19

(2) Measurements using Capacitor-type Dosimeters

Capacitor-type passive dosimeters No. 1 to No. 4 were irradiated in Site A and Nos. 5, 7 and 8, in site B. Due to the loss of a component, No. 6 was not used. No. 4 and No. 8 were oriented at 90° with respect to the others. TABLE XIV gives the results for the seven dosimeters, along with those for the active dosimeters irradiated in the same sites and counted over the same detector area.

TABLE XIV

Measurements Using Capacitor-type Passive Dosimeters

Site	Dosimeter type	Tracks /0.28 cm ²		ThC'/RaC'
		ThC'	RaC'	
A	Active*	72	74	0.92
	Passive No. 1	66	165	0.40
	No. 2	130	330	0.39
	No. 3	123	261	0.47
	Average	106± 22%	252± 19%	0.42± 7%
	No. 4	22	98	0.22
B	Active*	63	78	0.80
	Passive No. 5	53	91	0.58
	No. 7	108	121	0.63
	Average	81± 29%	106± 12%	0.61± 3%
	No. 8	38	165	0.23

* Track densities calculated for a 5 Lph active system.

- a) The ThC'/RaC' ratio for the dosimeters oriented 90° with respect to the other dosimeters is less than that obtained from the dosimeters installed in the vertical position.
- b) The difference in the ThC'/RaC' ratios at the two sites indicates variations in the site conditions.
- c) Efficiency of the RaC' detection (measured in terms of track density) is generally higher for the passive dosimeter than for the active system operating 5 L/h. Efficiency of ThC' may be less, which is considered to be due in part to the use of thicker absorber (Section 5.2.2(2)).
- d) The average dispersion of individual readings from the mean is about the same order for the mine and the radon (thoron) box. Usually, because of local effects in the radon (thoron) box due to its relatively small volume, mine test results are expected to be better. Actually, the present results seem to indicate the reverse.

(3) Measurements Using Electret-type Dosimeters

Electret-type passive monitors No. 1 and No. 2 were irradiated in site A and No. 3 and No. 4 in site B. TABLE XV gives the results.

TABLE XV

Measurements Using Electret-type Passive Dosimeters

Site	Dosimeter type	Track Density		ThC'/RaC'	Efficiency*
		ThC'	RaC'		
A	No. 1	15	13	1.15	17%
	No. 2	17	10	1.10	13%
B	No. 3	20	18	1.10	23%
	No. 4	18	17	1.10	20%

* Efficiency compared with the active system of 5 L/h (Average for both ThC' and RaC')

a) The ThC'/RaC' ratios are practically the same for all dosimeters.

b) The efficiency is, on the average, 20% of the efficiency of an active dosimeter operating at 5 L/h.

(4) Conclusions Derived from the Mine Test

1. Results from both laboratory and mine tests show that, using a capacitor-type dosimeter, the ratio ThC'/RaC' is constant to within 7% for detector in close proximity. However, the extent of the area for which the ratio is expected to be constant is still open to further investigation.
2. In general, the efficiencies (measured in terms of track density) of the capacitor-type and the electret-type dosimeters appear to be approximately 200% and 20% respectively, of the efficiency of an active dosimeter operating at 5 L/h.
3. The average dispersion of the track density from the mean, for units installed in the same area, is less than 30% for the capacitor-type and less than 20% for the electret-type dosimeters. It is believed that, in the capacitor-type dosimeters, the dispersion can be improved to within 20% by improving the geometry and the electrical insulation.

6. CONCLUSION AND RECOMMENDATIONS

Experimental results accumulated in the course of this project have been described in detail in Section 5. In Section 6.1, it is intended first to summarize the results in the context of the basic tests prescribed in the Statement of Work (Appendix A) and then to address the question of the feasibility of future designs. In Section 6.2, recommendations will be made regarding the approach which should be adopted in future development namely the choice of the plane source or volume source method as described in Section 2 and 3.

6.1 Summary of Results of the Basic Tests

1. The Use of Electrets

The electret does not appear to be a straightforward method of establishing the electrostatic efficiency enhancement especially in the mine environment (Section 5). There is no large scale commercial supply of electrets which have the effective potential required by this project. Even if the required electret were available, a simple, feasible method of washing or covering would be required for the mine use (Section 5.3.4). Use of the electret for radon or radon daughter dosimetry is currently limited to radon only (Section 5.3.4). Very few publications mention the use of electret for the measurement of radon (thoron) daughters. Kotrappa et al.⁽¹⁴⁾ reported a result using an electret as a detector. In this design, the electret undergoes a change of charge state due to the production of ion-pairs as a result of alpha ionization in the testing chamber. That is, the electret is not used for electrostatic enhancement. Rather than using electrets, it has been demonstrated in the basic tests that a charged capacitor can be used successfully in the hostile mine environment (Section 5.4).

2. The Use of CR39 as a Detector

The calibration test revealed that the alpha tracks of the CR39 detector are easily readable in the energy range from 1 MeV up to 5 MeV (or even higher) and within an angle of incident range of 0° to 55° (Section 5.1.1). This indicates the much higher efficiency of CR39 for the passive dosimeter application as compared with nitrocellulose (for instance LR 115 type II). The LR115 type II detector can only detect alpha particles of energy less than 4 MeV and angle of incidence less than 30° to normal, whereas the detection efficiency of CR39 for detecting ThC', RaC' and RaA is estimated to be 2 to 4 times higher than LR115 type II. Although the shape of the tracks in CR39 (Figure 19 to 58) vary according to energy and incident angle, this does not present any problems, since it has been found that automatic counting using image analysis is even easier than with the LR115 type II (Section 5.1.2). Finally, it is worthwhile to mention the CR39 is excellent for use with the system of electrostatic enhancement because it usually carries less charge than nitrocellulose.

3. Use of the Radon Diffusion Chamber

In Section 4.1.3, it was reported that the efficiency of RDC can be improved by applying electrostatic enhancement.

4. Use of the Total Absorption Method

In the basic test, the electrostatic induced plate-out method was used to approach a plane source condition. (Section 2.2.2) If a plane source condition can be assumed, differentiation of the ThC' from RaC' is straightforward by using the appropriate absorber.

The residual energy of alpha particles after passing through the absorber can be estimated quite accurately by using well known energy range relationships. TABLE XVI gives an example.

TABLE XVI

Alpha Energy Degradation Through Polycarbonate Absorbers

	Initial Energy MeV	Energy Expected After Passage Through	
		40 μ m Absorber	60 μ m Absorber
Rn	5.6	0	0
RaA	6.0	0.5	0
RaC'	7.68	3.9	0
ThC'	8.78	5.4	3.1

5. The etching conditions (6.25 N NaOH at 75°C) and the etching time (2 hours), were optimized such that the efficiency of track counting is the same for 3.1 and 5.4 MeV alphas at all incident angles from 0° to 60°.

6.2 Recommendations

It is suggested that the plane source method be continued as the first priority, although both plane source and volume source methods are worth further investigation.

(1) The Plane Source Method

So far, the plane source method using the capacitor prototype has demonstrated that electrostatic enhancement is effective and that the performance in the mine atmosphere is good. The only problem with the plane source method is the "position-sensitivity" of the RaC'/ThC' ratio. This problem is mainly related to variations in the charged fractions of the radon and thoron daughters in the mine atmosphere as was discussed in Section 2.2.2.

In Section 2.2.2, it was indicated that the forced plate-out situation may be different from the ordinary plate-out condition. Our mine test definitely showed that the efficiency of the dosimeter using the plane source approach can be more than three times higher in the mine (more than 150% of the efficiency of the active system, Section 5.4.2(2)) than in the ordinary atmosphere (~50% of the efficiency of the active system Section 5.3.3). In effect, this means that the dosimeter using the plane source approach actually monitors the radon (thoron) progeny level in the mine atmosphere, following the definition of Working Level.

We believe that the high dispersion of results of the mine test using the capacitor prototype is mainly due to variation in the geometry of the prototypes. Once we have the quality of the prototype well controlled, it will be worthwhile to have a thorough and reliable study of the position sensitivity of the RaC'/ThC' ratio in the mine atmosphere, and larger scale tests of the improved dosimeters.

Three major problems remain to be solved:

- (a) Improvement of the precision; in other words reduction of the dispersion from the mean value.
- (b) Determination of the effect of the size of the stope on the ThC'/RaC' ratio, and
- (c) Simplification of the field-charging process.

It is proposed to solve the above problems by the following developments:

- (a) Quality control of the capacitor prototype, with emphasis on
 - 1. Improvement in electrical insulation
 - 2. Better control of detector geometry.

It is quite certain that the dispersion of the testing data is not due to statistics but to inadequate quality control. When the precision of the dosimeter has been improved, it will be possible to obtain a more accurate picture of the spatial variation of the ThC'/RaC' ratio.

- (b) Research into a means of maintaining a constant potential above the detector, possibly by a miniaturized built-in high-voltage supply.

(2) The Volume Source Method

Basic experiments which will facilitate further development of the volume source method are listed below:

- (a) Use of the RDC
Benton's Working Level ratio method (Section 2.1.2) may be a reasonable approach if 96% of the radon (thoron) progeny is in the atmosphere. Under this condition, the local effect is mainly contributed by the charge fraction of the alpha emitter if the electrostatic enhancement device is used. There is the possibility of obtaining a standard Working Level ratio such that WL can be calculated from the radon intensity determined by RDC.
- (b) Automatic counting as a means of scanning detectors of large areas.
- (c) Accumulation of enough standard track data covering a wide range of energy and angle of incidence for the optimization of absorbers.

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APPENDIX A

STATEMENT OF WORK

1. Objective

To study the feasibility of designing and developing a passive personal dosimeter, which incorporates an allyl diglycol carbonate plastic (CR39) detector, for use by uranium miners. The passive dosimeter will be referred to an active dosimetry system for local calibration and will be designed to identify and measure, separately, the decay products of radon and thoron.

2. Statement of Work

(This is based on the section of the proposal entitled "Proposed Work", pg. 6, item 2.1, "Basic Tests". (See Below.))

- a) Investigate the use of the electret technique to implant a negative charge in a polycarbonate (mylar) absorber.
- b) Investigate the suitability of CR39 for alpha detection.
- c) Investigate the use of the total absorption method for the differentiation of radon, thoron and their daughters.

Basic Tests

The primary scope of the tests is to accumulate the following information:

1. Use of the electret technique to implant a negative charge in the polycarbonate (mylar) absorber. This absorber will serve the dual purpose of:
 - a. keeping the detector surface clean;
 - b. improving the detecting efficiency of the radon (thoron) daughters by the presence of a favourable electric field.
2. Use of CR39 as the total alpha detector. For the total alpha detection method, CR39 is the best choice among different track-etch detectors since the track geometry is not too sensitive either to energy or to the angle of incidence.
3. Use of the radon (thoron) diffusion chamber and the application of total absorption method for the differentiation of radon, thoron and their daughters.

APPENDIX B

ANL WORK WITH HIGH-FIELD ELECTRETS

Our work in electret charging led us to contact the Argonne National Laboratory in the United States which has had experience in high-field electret charging techniques. The High Energy Physics Group of the ANL has tried to produce a super highly charged electret for the control of their accelerator beam. For this purpose, the electret should be charged to 100 times the charge of the commercial electret used in electrostatic microphones (the later being typically 0.25 kV, measured using the charge locator, a value which is only one-tenth of that used in our capacitor prototypes).

ANL has worked two years on electret charging techniques. The following information was provided by ANL:

1. ANL was partially successful in charging electrets to the level suitable for our purposes, but could not reach the higher charge level necessary for their work.
2. When the electret is removed from the oven, the measured field is exceedingly high. After the surface charge is washed away, only a small fraction of charge remains; this is the effective electret charge. The field is diminished when exposed to air, but is restored after the surface of the electret is cleaned.
3. The substrate should be heated to the softening point before the charging potential is applied. Below the softening point, charging will not be effective. It is believed that most plastic film substrates can be charged as electrets; of these, teflon seems to be the easiest to charge.
4. The charging equipment should be absolutely clean. An ordinary oven with fire brick lining should not be used because, at high temperatures, dust is produced at the brick surface. The inside of the oven should be fitted with a suitable lining. ANL showed us the oven inside their clean room.
5. During charging, pure nitrogen under positive pressure is made to flow continuously through the oven.

The findings of ANL are in agreement with our experience.